THE EFFECT OF MATERIAL TRANSFER DEVICES ON HMA MATERIAL UNIFORMITY AND RIDE QUALITY

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By

Mary Stroup-Gardiner
Frazier Parker
Kristy Burns Harris
Barkley Williams

National Center for Asphalt Technology
Auburn University
Auburn, Alabama

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EXCUTIVE SUMMARY

Alabama Department of Transportation (ALDOT) recently started to require contractors to use a material transfer device (MTD) in the construction of hot mix asphalt (HMA) pavements in order to minimize segregation. While some research has been done that indicates that the use of a MTD will minimize both temperature and gradation segregation of the mix components once the mix leaves the HMA plant, no research has been done to evaluate the impact of a MTD on initial ride quality.

The objectives of this research were to document the influence of MTDs on improving both mix uniformity (i.e., lack of segregation) and initial ride quality. The scope of this project included the evaluation of four Alabama HMA projects constructed during the 2001 and 2002 paving seasons. On three of the four projects, both the binder and surface courses were evaluated. Areas of non-uniformity were identified during construction using an infrared camera, with areas having a temperature difference of more than 19^{o}F being classified as non-uniform. Both ride quality and uniformity after construction was completed was identified using data from the Auburn University Roadware inertial profiler.

Results show that the inclusion of a MTD in the HMA paving train can significantly reduce the non-uniformity of the mix as measured by either temperature differences or texture variations. A MTD also results in significantly smoother HMA pavements. These conclusions are based on the paving operations moving continuously. Any stops, with or without a MTD, will result in both more non-uniform (potentially segregated) areas and a rougher ride.

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INTRODUCTION

Research has found that temperature differentials of more than 19°F (10°C) indicated potentially segregated areas in the hot mix asphalt (HMA) mat. The higher this temperature differential, the more likely segregation is present, which in turn leads to differential material stiffness, density and life expectancy. The definition of segregation includes both materials segregation and temperature segregation. It is likely that factors such as the screed settling during a stop and the differential compaction of the HMA in areas with different temperatures, either from material or temperature segregation, will lead to anomalies in both texture and ride quality (Stroup-Gardiner and Brown 2000).

The transportation of mix from the plant to the job site is the first step in producing high quality ride and pavement performance. Trucks should not be loaded with single dumps from silos, as this contributes to segregation. Mix delivery must be planned properly to have sufficient material for continuous movement of the paver. Also, trucks should not bump the paver when dumping the mix into the hopper, which can lead to localized rough ride. Trucks should not be allowed to run empty and a uniform head of material with consistent temperature at the screed will ensure that the resistance on the screed remains constant. All of these factors contribute to a smooth riding pavement with a good life expectancy (Janoff 1997).

A method recently introduced to help achieve continuous movement of the paver and a uniform flow of consistent mix is to include a material transfer device in the paving train. The material transfer device eliminates stopping of the paver to connect with haul trucks and provides some surge capacity to smooth out erratic, or non-uniform, mix delivery. Also, the material transfer device or hopper insert remixes the asphalt concrete to improve its temperature and gradation consistency as delivered to the paver. More consistent mix should reduce segregation and temperature variation in the mat, which in turn should increase smoothness.

BACKGROUND

The public's satisfaction with a roadway is primarily based on the smoothness (i.e., the absence of roughness) of the pavement. The first thing the average motorist notices about a smooth pavement is there is less noise than a rough pavement. Also, after a long trip, motorists realize that they are not as tired from the vibrations that would result from a rough pavement. Smooth pavements that the public demands start with smooth as-constructed pavement surfaces. Research has shown that initial smoothness is important to both future smoothness and pavement life. The process of achieving quality ride characteristics starts at the hot mix asphalt (HMA) plant and is a continuous, uniform, and coordinated process through mat compaction. Consistent mix temperature and continuous paving machine operation are critical parameters. The ideal situation is that the mat, with uniform and consistent temperature, is laid down in a continuous operation with minimal interruptions. Incentives through bonus payments to contractors help produce smoother pavements have been estimated to increase pavement life by 10% (Massucco 1999).

Ride Quality

A study of the relationship between initial smoothness and pavement life used 10 years of historical data from over 400 sections of roadway in Arizona and Pennsylvania (Janoff 1991). The data included initial pavement smoothness, annual measurements of smoothness, several forms of pavement distress, such as patching, cracking, rutting and deflection, and annual maintenance costs. Through statistical analysis, it was shown that the initial smoothness of a pavement is related to both long-term roughness and cracking. Pavements that are initially smoother, even by a small amount, will have significantly smaller rates of increase in roughness and cracking than pavements that are initially rougher. Another effect determined in this study was that pavements that are initially smoother have lower average annual maintenance costs. Average annual savings are nearly $1200 per mile when initial smoothness, or initial Profile Index (PI), is reduced by 10 inches per mile (158 mm/km).

Another study (Smith, et al 1997), using state highway agencies' information on the initial and in-service smoothness of pavements, showed that initial smoothness had a significant effect on the in-service smoothness for all pavement types. Predictive models from this study indicate a 25% increase in initial smoothness has a resulting 9% increase in pavement life. Results from this study were included in a larger study that added data from the Long Term Pavement Performance (LTPP) database. A multiple linear regression equation displays a strong indication of the effect of the initial smoothness on future smoothness:

$$S_t = a_0 + a_1 S_i + a_2 t$$

S_t is the pavement smoothness at time t in inches per mile, a_0, a_1 and a_2 are regression coefficients, S_i is the initial pavement smoothness or Roughness Index (RI), and t is time, or age, in years since construction or overlay to time of testing. The value of a_1 represents the slope of the regression line between future and initial pavement smoothness and ranges from 0.85 for Portland Cement Concrete (PCC) pavements to 0.60 for asphalt overlay of an existing asphalt pavement (AC/AC) projects. For Alabama HMA pavements, 13 out of 14 projects, or 93 percent, showed a significant correlation between initial smoothness and smoothness measured during the pavement's service life.

A field test was conducted to test the effect of underlying surface smoothness on as-constructed overlay smoothness (Fernando 1997). This field test used test sections in Texas with a wide range of pavement conditions to determine smoothness specifications for overlays. The pavement condition on each project was determined using data from the Texas Department of Transportation's (TxDOT) Pavement Management Information System. To ensure the smoothest possible overlay, some of the worst sections were milled, adequate material supply was provided at the jobsite to minimize delays, and truck drivers were careful not to bump the paving machine. The results showed that specifications for new pavements could be used for overlays as long as some guidelines for surface preparation are followed. Surface preparation before overlay is necessary when:

- Ruts deeper than ½ inch (13 mm) cover more than 20 percent of the surface area,

- Segments have more than one failure (failure not defined in study) per 0.6 mile (1 km), or
- More than 50% of the surface area is patched.

To determine factors that affect the ride quality of overlays, the Virginia Department of Transportation conducted a study with roughness surveys of 2,650 lane-miles of roadway. The study variables were limited to those that could be controlled by the contractor, and a database was developed to help in the analysis. The factors that were found to affect overlay smoothness were: (1) the roadway functional classification, (2) the ride quality of the underlying pavement, and (3) a special provision for ensuring smoothness. This special provision included using the International Roughness Index (IRI) as the smoothness measurement and pay adjustments, incentive/disincentive, based on the IRI. An overlay IRI of 60 to 70 inches per mile (950 to 1100 mm/km) is the range for 100 percent pay, with IRI of over 100 inches per mile (1580 mm/km) requiring corrective action. Lower overlay IRI values constitute the incentive part of the provision. Functional classification is the grouping of highways by the character of service they provide. The hierarchy of this functional system includes: principal arterials, minor arterials, collectors, and local roads and streets. The effect of this factor is that the higher classification roadways have smoother overlays. And with a smoother underlying pavement, the results show that the overlay will be smoother. Finally, the addition of the special provision with an incentive/disincentive clause motivates the contractor to produce smoother pavements.

There were too few differences in overlay thickness to determine if this variable affected ride quality. Mix type, an additional structural layer between base and overlay, or multi-layer overlay, milling and the time of paving (night or day) did not affect overlay smoothness (McGee 2000).

Uniformity of the HMA Mat

A method to help achieve continuous movement of the paver and a uniform flow of consistent mix is to include a material transfer device (MTD) in the paving train. The MTD eliminates stopping of the paver to connect with haul trucks and provides some surge capacity to smooth out erratic, or non-uniform, mix delivery. Also, the MTD or a hopper insert remixes the asphalt concrete to improve its temperature and gradation consistency as delivered to the paver. Research on NCHRP Project 9-11 found that both temperature differentials of more than 10EC (19E F) in hot mix asphalt concrete mats, and significant changes in the surface texture are associated with segregated areas (Stroup-Gardiner and Brown 2001). This research also showed the greater the non-uniformity (either temperature or texture) the more likely segregation will occur followed by a noticeable increase in pavement distresses in the segregated (non-uniform) areas. While it was also hypothesized that areas with non-uniform properties would also have a localized rougher ride, the original study did not include an evaluation of ride quality.

A Texas field test attempted to determine if several material transfer and remixing devices could produce a smoother, less segregated pavement than conventional windrow paving equipment (Asphalt Contractor 2000). The five consecutive days experiment used a TxDOT type A mix, which was prone to segregation. Characteristics of a type A mix are: a gradation curve with 60 percent of the aggregate 0.375 inches (10 mm) or larger, 100 percent passing 1.5 inches (38 mm) and very few fines. In this test, all material was deposited in a windrow. The equipment used the first day, a BG-650 windrow elevator and BG-260C asphalt paving machine (no remixing), was considered standard equipment and used to compare the performance of other equipment. On the following days, four different types of material transfer and remixing devices, identified in Table 1, were added to the paving train. The results from density analyses indicated:

- Segregation by improper loading of delivery trucks or when dumped from the trucks was not effectively reduced, nor could the material be remixed to reduce segregation, by any of the equipment.
- Proper paving practices and well-trained crews have a major impact on quality and can produce pavements that meet specifications using any method.
- There were no correlations between paving equipment, mat segregation and mat density.
- Infrared cameras can be used to measure surface temperature variation without correlation to density and smoothness.

Table 1. Machinery Variations Used for Trials.

Day 1	BG-650 windrow elevator and BG-260C paver (control)
Day 2	Roadtec SB2500 material transfer vehicle and BG-260C paver with hopper insert (Roadtec picked up windrowed mix)
Day 3	Lincoln 880 windrow elevator and BG-260C paver with Lincoln pug mill hopper insert
Day 4	Cedarapids MS-2 windrow elevator and CT 461 remixer paver
Day 5	BG-650 windrow elevator / Blaw-Knox MC-330 mobile conveyor and BG-260C paver with Blaw-Knox pug mill hopper insert

Three types of segregation were found in the testing: cyclical end-of-load segregation, random patch segregation and longitudinal stripe segregation. It was discovered that, for three of five days, trucks were loaded with a single dump, and therefore large amounts of coarse material were found at the end of each windrow dump causing cyclical end-of-load segregation. Failure to maintain a constant level of mix in the hopper caused coarse aggregate to roll toward the outside when filling and resulted in random patch segregation. Stripe segregation was a result of improper adjustment of the paver augers.

Material Transfer Devices

There are two commonly used material transfer devices by Alabama HMA contractors: These are units manufactured by 1) Blaw-Knox, and 2) Roadtec.

Blaw-Knox

The haul trucks dump their load into the MC-330 Mobile Conveyer, which has a 30-ton storage bin. The mix is then transported up a non-slip conveyer belt and is dumped directly into the 14-ton hopper mounted on the front of the paver. The MC-330 does not have an internal auger that remixes the asphalt; therefore the only purpose of this MTD is to move the mix to the paver enabling it to continuously pave without stopping. Since the mix is not agitated by the MTD, this eliminates the need for a ventilation system on the MTD, which can actually lower the temperature of the mix by increasing the airflow over the mix. The paver-mounted surge bin has two transverse mixing augers that re-mix and blend the asphalt before being placed on the road. The MC-330 has few high-tech parts; therefore it infrequently breaks down and it is easier to fix than the Roadtec SB-1500B if it does break down. Figure 1 shows the dimensions of the MC-330 Mobile Conveyer and Figure 2 is an image of the MTD being utilized on a paving job (Blaw-Knox 2000).

Roadtec

Haul trucks dump into the front of a SB-1500B and a converging auger, with the help of vibrators, moves the mix up a conveyer into a 25-ton surge bin. Located inside the surge bin is a triple-pitch-segmented auger that remixes the asphalt resulting in a mix of even temperatures before another conveyer belt discharges the mix into the paver. A 15- to 20-ton hopper attaches to the front of the paver and enables the MTD to move away from the paver with enough material to continue paving until the SB-2500B returns. Another bonus feature on this model is a fume extraction system that removes fumes and hot air to exhaust pipes and away from the paving crew. The dimensions of a SB-2500B are displayed in Figure 3 and the utilization a Roadtec SB-2500B on project 4-1 is shown in Figure 4 (Roadtec 2002).

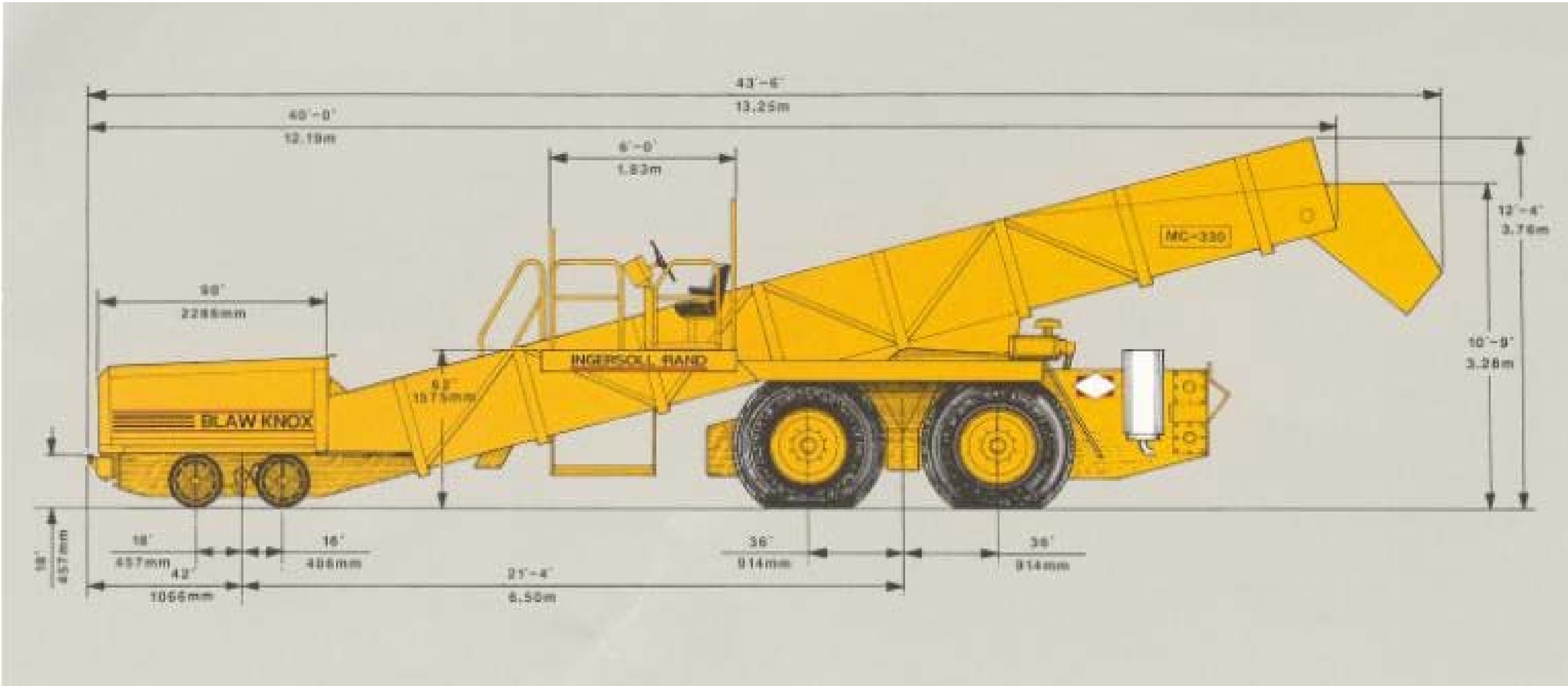

Figure 1. Dimensions of a Blaw-Knox MC-330 (Blaw-Knox 2000).

Figure 2. Blaw-Know MC-330. (The red arrows show the path that the mix follows).

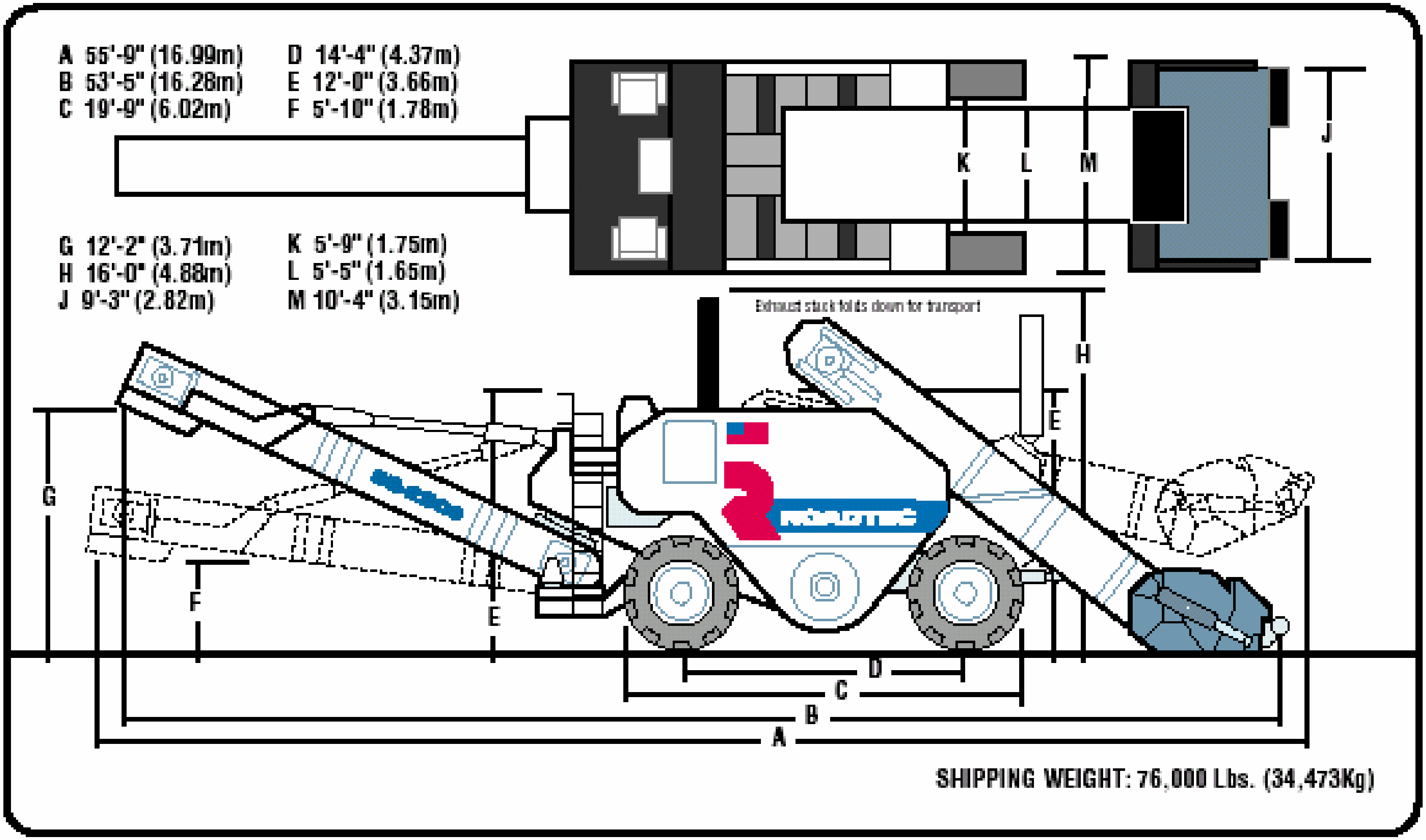

Figure 3. Dimensions of a Roadtec SB-2500B (Roadtec 2002).

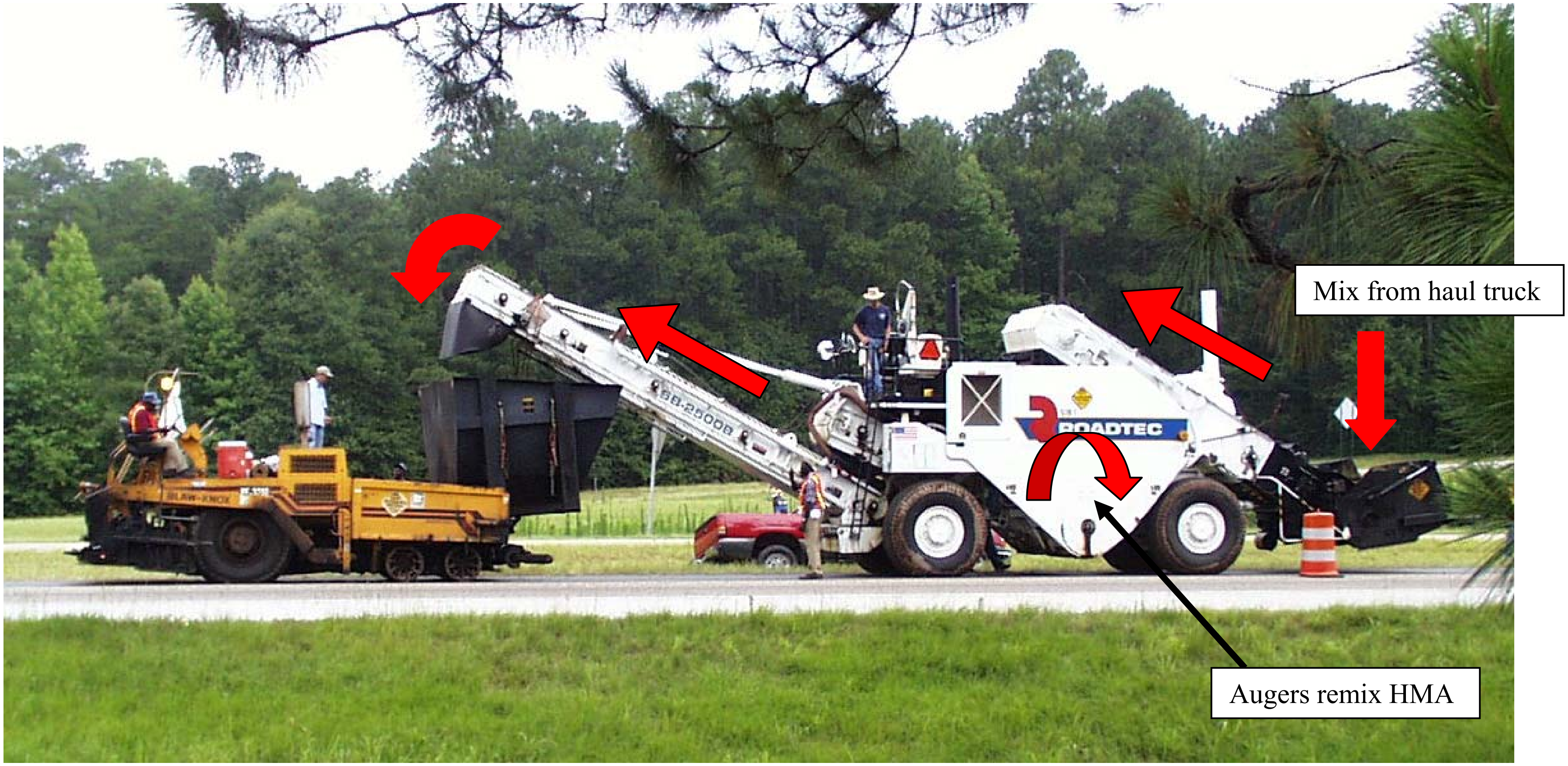

Figure 4. Roadtec SB-2500B- The red arrows show the path that the mix follow.

RESEARCH PROGRAM

Objectives

The objectives of this research were to determine the effect of material transfer devices on:

- Non-uniformity of HMA.
- Initial ride quality.

Localized areas of non-uniformity were identified during construction with infrared thermography and changes in surface texture measured immediately after construction was completed. Temperature differentials during construction were used to identify localized areas of non-uniformity in the HMA mat. The longitudinal distance from the start of the test section as well as the time each area was logged for correlation with IRI values from the Roadware van. Changes in surface texture, also an indication of non-uniformity in the HMA mat, were also evaluated as an indicator of areas of potentially accelerated pavement distresses.

Scope

Projects were selected based on the contractors willing to pave both with and without a material transfer device on existing ALDOT contracts. HMA mix variables such as the maximum aggregate size and the binder type were included in the study by evaluating different lifts on the same construction projects. Three Alabama construction projects were evaluated with and without a material transfer device for both the binder and surface mix lifts. While all of the mixes for these three projects met Section 424 bituminous mixture ALDOT specifications, the binder lifts had a 1 inch maximum aggregate size and used a PG 76-22 binder (ALDOT 2001). The surface mixes had a maximum aggregate size of ½ to ¾ inch and used a PG 67-22 binder. A fourth project was evaluated for only the binder lift. This mix was a stone matrix asphalt (SMA). Designations for each mix for each project are used to indicate project and lift. For example Project 1-2 indicates the second lift tested (i.e., surface mix) for project 1.

With the exception of Project 3-1, all of the areas tested were at least 3,000 feet long. Project 3-1 lengths were shorter due to both equipment and weather problems; this was also the only section that was paved during the winter season. The Project 3 contractor was also the only one that used other than a Roadtec MTD. Most of the projects had paving lane widths of about 12 feet; Projects 2 and 3 widths were 14 and 16 feet, respectively. Project 1-2 was the only section that was placed over non-milled old pavement.

An infrared camera used to monitor and mark potentially non-uniform areas during construction. A walking distance wheel was used to determine the longitudinal location of any areas with differences in the mat temperature of more than 19^{o}F. Distances were entered into the field logs.

Once construction was completed and before the sections were opened to traffic, Auburn University's Roadware ARAN inertial profiler was used to determine IRI in both wheel paths and the surface texture in the right wheel path. IRI values were reported in inches/mile for every 26 feet of the test sections.

PROJECT DESCRIPTIONS

During this study, four separate HMA paving projects in Alabama were tested for this project (Figure 5). Three of the four projects used the construction of both the binder and surface mix for evaluating the influence of a MTD on mix uniformity (i.e., uniform temperature, surface texture) and ride quality (i.e., IRI). Only the binder mix was tested for Project 4 due to delays in construction.

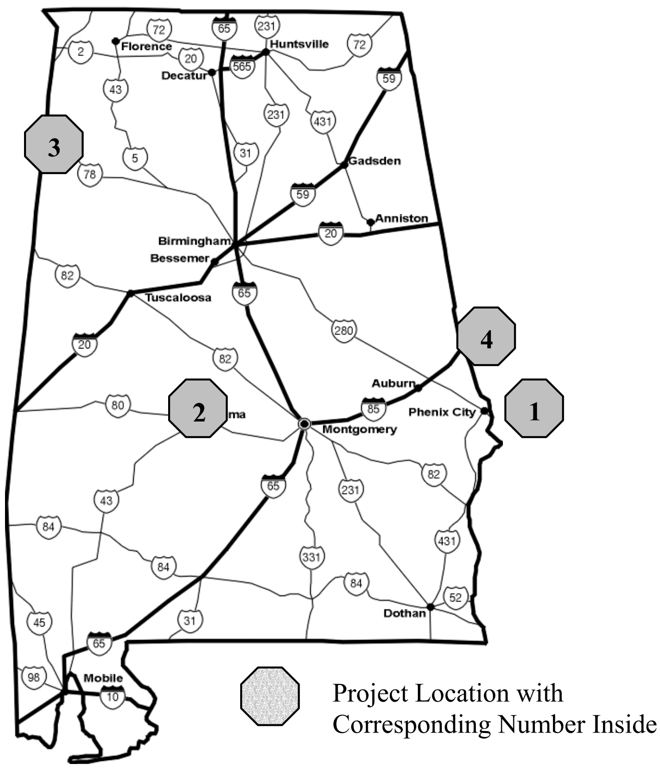

Figure 5. Alabama Map with the Locations of the Projects.

Table 2 summarizes the lengths constructed with and without a material transfer device (MTD) for each project, construction dates, type of surface preparation.

Table 2. General Project Information.

Project	MTD used	Date of Paving	Total Length (feet)	Lane Width (feet)	Temperature (^{o}F) high/low	Weather	MTD Manufacture	Surface Preparation
1-1 Binder	no	7/23/01	3139	11.5	85	Clear, humid (night)	None	Milling & Chip Seal
	yes	7/25/01	2230	12.5			Roadtec	
1-2 Surface	no	8/15/01	3997	11	85	Clear, humid (night)	None	Patchwork & Chip Seal
	yes	8/14/01	4100	11			Roadtec	
2-1 Binder	no	8/23/01	2950	12	93	Clear, humid	None	Milling
	yes	8/23/01	2950	12			Roadtec	
2-2 Surface	no	9/10/01	3140	14	93	Clear, humid	None	None
	yes	9/10/01	2825	14			Roadtec	
3-1 Binder	no	12/12/01	1813	16	70	Clear, cloudy	None	Milling
	yes	12/12/01	1130	16			Blaw-Knox	
3-2 Surface	no	5/23 and 5/24/02	4201	16	75	Clear, dry	None	None
	yes	5/23/02	6022	16			Blaw-Knox	
4-1 Binder	no	6/24/02	3877	12.5	90	Clear, humid	None	Milling Chip Seal
	yes	6/24/02	2880	12.5			Roadtec	

Table 3 summarizes a range of HMA information. All of the binder course mixes were constructed using a polymer modified PG 76-22 binder and an aggregate gradation with a 1 in. maximum size aggregate. Surface mixes used a PG 67-22 with a maximum size aggregate of ½ to ¾ in; the gradations for the surface mixes were finer than for the binder mixes. Project 4 used an SMA gradation, which makes it the coarsest gradation evaluated for this project.

Table 3. Mix Properties as Reported by Paving Contractors.

Binder Grade Type Mix	Project 1		Project 2		Project 3		Project 4
	Binder	Surface	Binder	Surface	Binder	Surface	Binder
	PG 76-22 424	PG 67-22 424	PG 76-22 424	PG 67-22 424	PG 76-22 424	PG 67-22 424	PG 76-22 423
ESAL Category	Range E	Range C/D	Range E	Range E	Range E	Range C/D	SMA
Asphalt Content, %	3.9	5.7	4.1	4.6	4.75	5.5	5.5
AC Req'd/Ton	86	114	82	92	95	110	110
Max Specific Gravity	2.637	2.492	2.530	2.507	2.454	2.576	2.549
Unit Weight (lbs.)/ft^3	157.7	148.9	151.2	149.7	146.5	153.8	152.3
VMA, %	13.0	16.3	13.7	14.0	13.8	15.0	17.0
TSR	0.90	0.86	0.86	0.90	0.85	0.88	0.86
Anti-strip additive, %	---	---	---	0.50	---	---	---
Effective AC Content, %	3.65	5.37	3.90	4.35	4.38	4.68	5.4
Dust/Asphalt Ratio	1.07	1.01	0.95	0.95	1.02	1.13	---
Coarse Agg. Angularity	100/100	100/100	98/96	98/96	99/98	100/100	100/100
Fine Agg. Angularity	49	46	45	45	45	45	47
Agg. Specific Gravity	2.792	2.693	2.683	2.675	2.608	2.765	2.784
Max. Aggregate size	1"	3/4"	1"	3/4"	1"	1/2"	1"
Sieve Size	**Cumulative Percent Passing, %**						
1”	100	100	100	100	100	100	100
3/4”	90	100	99	100	98	100	90
1/2”	75	95	88	96	89	100	74
3/8”	62	82	78	87	83	97	54
#4	43	64	55	61	64	72	28
#8	27	53	33.3	38.5	45	47	21
#16	20	42	22.1	25.3	34	34	17
#30	15	29	15.1	17.9	26	28	15
#50	13	15	7.8	9.3	15	14	11
#100	6	9	5	5.8	8	8	9
#200	3.9	5.4	3.7	4.1	4.5	5.3	8.0

---: no data available

Table 4 provides a general idea of the type and percentage of aggregate sources used for each of the projects. Project 1 used various sources of limestone aggregates while Project 3 used a combination of limestone and sandstone. Project 2 used a combination of limestone and crushed gravel. All of the projects, except Project 1, used some percentage of reclaimed asphalt pavement (RAP).

Table 4. Types of Aggregates Used as Reported by the Paving Contractors .

Material	Percent of Aggregate Stockpiles Used in Each Mix						
	Project 1		Project 2		Project 3		Project 4
	Binder	Surface	Binder	Surface	Binder	Surface	Binder
Slag						25	
#57 Limestone	33						30
# 67 Limestone			26				
# 67 Sandstone					20		
#78 Limestone	33	25		14			
#78 Granite		15					44
½" Crushed Gravel				24			
#8910 Limestone	19		30	21	33	16	
#8910 Sandstone					22	35	
Coarse Sand		30	15	12	15	12	
M10 Granite	14	10					
Pea Gravel			14	14			
Baghouse Fines	1	1					
Fly Ash							5
Fibers							0.3
RAP			15	15	10	12	10

Project 1

Projects 1-1 and 1-2 were in an urban area of Phenix City in east Alabama on US 280 / 431 (Figure 6). This area is a four lane with a grass median and frontage roads on both sides. The project involved rehabilitation of the mainline and frontage roads with hot-mix asphalt (HMA) overlays. Because of traffic volumes, paving was done at night from approximately 8 pm to 3 am. The project used a Roadtec 2500 material transfer vehicle, and compaction was done with a vibratory breakdown roller factored by a steel wheel finish roller. The haul time of the mix was approximately one hour.

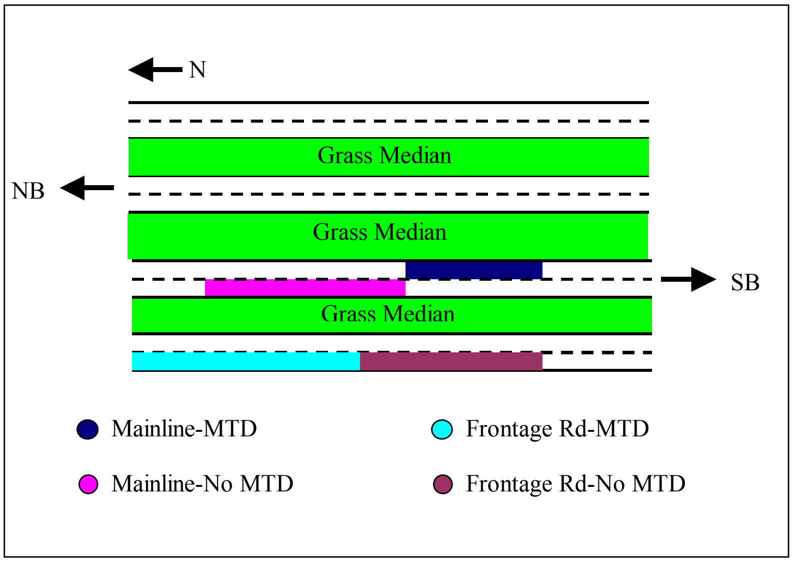

Figure 6. Project 1 Layout.

Project 1-1

Without MTD: Both nights an upper layer binder mix with a polymer modified asphalt and a maximum aggregate size 1" was laid on top of freshly milled and chipped sealed lanes. The mix designed for an ESAL range E was placed at a rate of 220 lb/yd^2, and was compacted using a vibratory breakdown roller with a steel finish. Traffic control did not begin until 7 pm on the night of August 22, 2001 and the paving company finished around 6 am on August 23 when all four lanes had to be reopened for traffic. Paving started at the north end of the outside southbound lane without a MTD and continued for 3,140 feet.

The second truck of the night had a spillage as it tried to lock up with the paver. The paver was used to feather out the spill prior to paving. In the same night, the paver had to stop an additional two times, besides the brief stops for haul trucks, to lower the lights, once to go under traffic lights and a second time to go under a power line.

With MTD: Beginning at 1 am on August 25, a Roadtec MTD was used to pave 2,230 feet of the inside southbound lane. Unlike the first night, a ski was used to control the screed. Employing the MTD enabled the paver to maintain a continuous forward movement. However, four stops were made by the paver while waiting for additional haul trucks to arrive.

Project 1-2

About a month later the surface mix, project 1-2, was placed. This time the frontage road on both sides of the mainline road were resurfaced. Before an overlay could be placed, various areas had to be patched and the whole area was chip sealed. The sections paved were the outside lanes of the west frontage road. At a rate of 165 lb/yd^2, a 424 Superpave surface mix with a designed ESAL range of C/D and a maximum aggregate size of ¾" was placed. The average width of the lanes was 11 feet, but throughout both nights a screed was extended to accommodate numerous driveways and parking areas. On the first night a Roadtec MTD was used to lay approximately 4000 feet. The next day construction continued from the joint and another 4100 feet of asphalt was placed without the MTD.

Project 2

Both the binder and the surface layer (Project 2-1 and 2-2) were placed on a stretch of US80 that is a four-lane highway divided by a grass median in Selma, Alabama as shown in Figure 7. This area of highway was being repaved because of the extent of rutting that had occurred due to the truck traffic in the area. The paving on this site occurred from about 8 am to 4 pm on hot, sunny days in late August and early September with highs up to 90^{o}F. An unusual aspect to this site was that the asphalt plant was over one hour away, which resulted in the plant mixing the asphalt at higher temperatures than usual to compensate for the long haul distances. The temperature of the asphalt behind the paver usually averaged between 320 and 340°F with a record high of 378°F. The Selma project paving operation included a Blaw-Knox paver and a Roadtec 2500 material transfer device. The mat compaction included two vibratory rollers and a steel wheel finish roller.

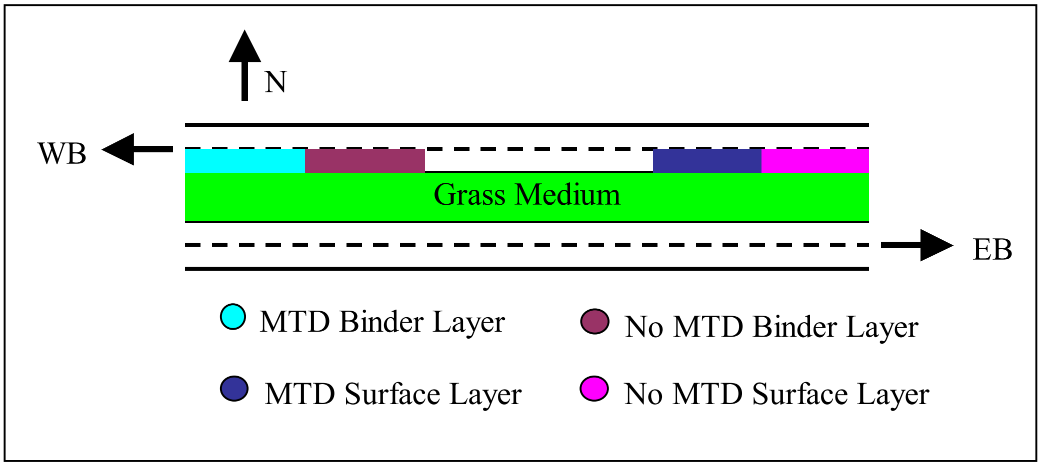

Figure 7. Layout of Project 2-1 the Binder Layer .

Project 2-1

The binder test section was the 12-foot westbound inside lane. The 424 binder mix, designed for ESAL range E, was placed at a rate of 225 lb/yd^2 with a maximum aggregate size of 1 inch. Before the binder layer could be laid, the area had to be milled. After 3000 feet was laid without the employment of a MTD, another 3000 feet was paved using a Roadtec MTD. Two vibratory rollers and a steel finish roller aided in the mat compaction. Throughout the day the paver had to stop numerous times to wait for haul trucks to arrive at the site.

Project 2-2

The surface test section was a 6000-foot continuous section with the latter 3000 feet utilizing the Roadtec MTD. Since a two-foot shoulder was included in this section of paving, two extensions had to be utilized resulting in a 14-foot width. The test sections were located on the inside westbound lane starting at the east end of the site. Designed for ESAL range E and a maximum aggregate size of ¾ inch, the 424 mix was placed at a rate of 165 lb/yd^2.

Project 3

Projects 3-1 and 3-2 are located on a four lane passing area with a grass median on rural highway US82 outside of Reform, a small northwest Alabama town. Figures 8 and 9 are layouts of the paved areas. A Blaw-Knox Mobile conveyor with a pugmill hopper insert was the MTD used on the project, and two vibratory breakdown rollers and one steel wheel finish roller performed the mat compaction. For both projects 3-1 and 3-2, a four-foot screed extension on the left and a two-foot one on the right created a paving width of 16 feet.

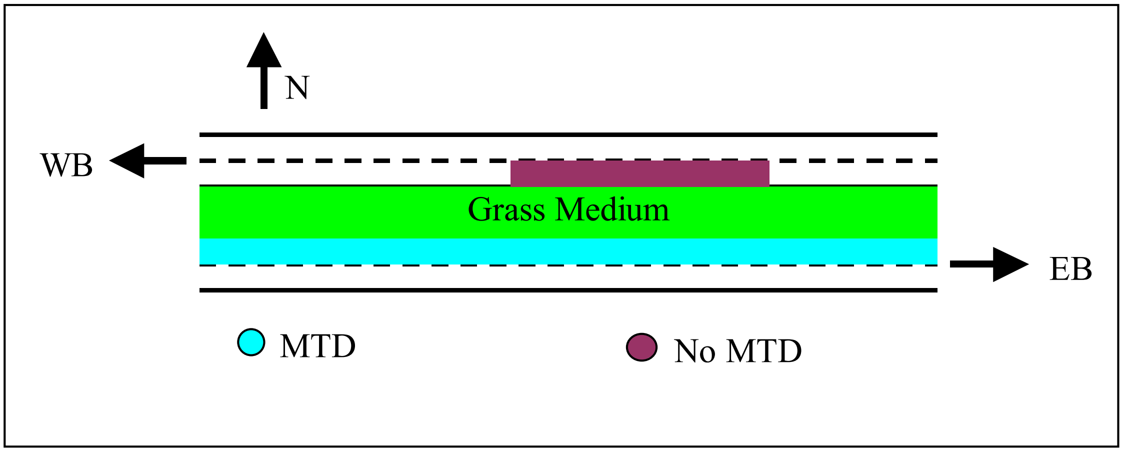

Figure 8. Layout of Project 3-1 the Binder Layer.

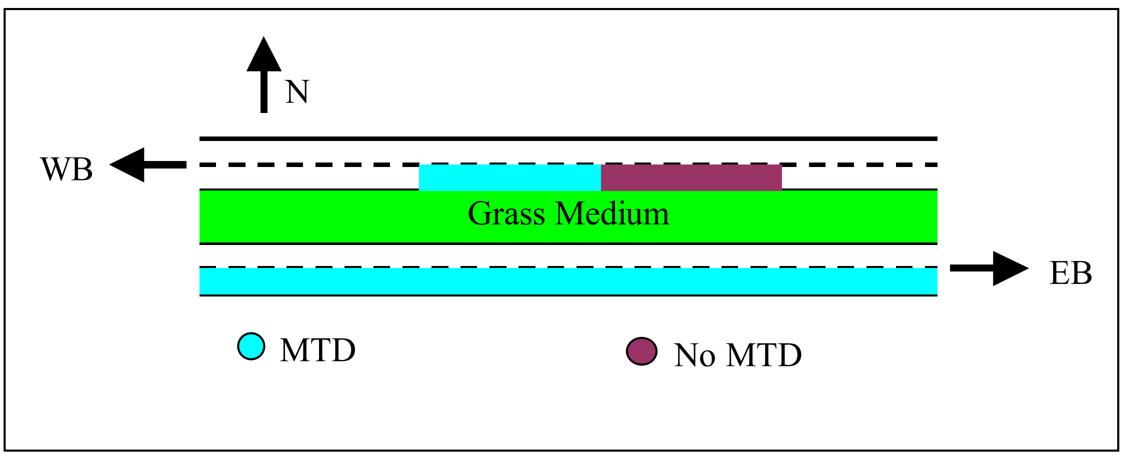

Figure 9. Layout of Project 3-2 the Surface Layer.

Project 3-1

For the day the binder section was constructed, the weather was an above normal December day with temperatures of approximately 50°F, a light breeze, and high humidity. A light rain occurred for a few minutes while paving with the MTD. The 2,900-foot test section was located on the inside westbound lane. The first 1,800 feet was paved without the MTD, and then the next 1,100 feet a Blaw-Knox MTD was added.

There were numerous stops being made by the paver, especially in the MTD section, due to a lack of haul trucks. The binder mix designed for ESAL range E was a fine-grained mix with a maximum aggregate size of 1 inch placed at a rate of 220 lbs/yd^2.

Project 3-2

The finest mix of all the projects was incorporated with a maximum aggregate size of ½ inch. The mix, designed for ESAL range E, was placed at a rate of 110 lbs/yd^2. Both days were sunny spring days with a temperature range of about 60 to 80°F. On the first day of paving from about 1 pm to 5 pm approximately 6000 feet of asphalt was laid in the inside eastbound lane using a Blaw-Knox MTD. In addition to the 6000 feet, approximately another 650 feet was laid in the next hour without using the MTD in the inside westbound lane. Starting at the joint from the night before, from 8 am to 10 am, another 3,500 feet was laid without the MTD. Both days, trucks were lined up and only occasional paver stops occurred towards the end of each section.

Project 4

Project 4-1 is located on I-85 outside of Auburn, Alabama and only a binder layer was used for testing. The layout of this project is shown in Figure 10. Paving took place on a hot humid day with temperatures reaching approximately 95°F. The section was milled and chip sealed before the binder layer was placed. The SMA mix was laid at a rate of 220 lbs/yd^2 with a maximum aggregate size of 1 inch. One vibratory roller and one steel wheel finish roller was used in the mat compaction of the 12.5 foot width lane. There was a wedge lock extension on each side with an additional ½ foot hydraulic extension on the left side.

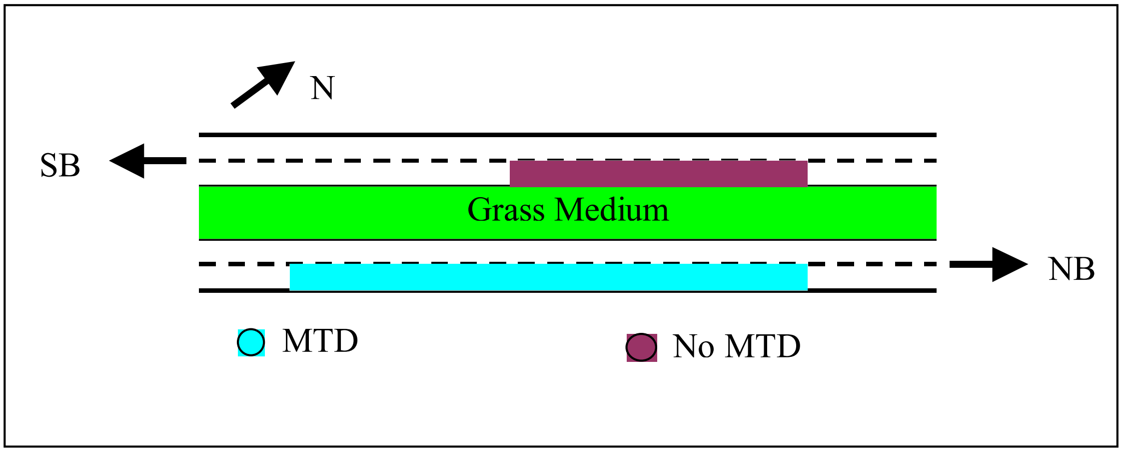

Figure 10. Layout of Project 4.

The inside lane of the northbound highway was first paved without using a MTD. On the 3,900-foot test section, the paver stopped briefly between each load and once briefly to lower the truck bed to go under an overpass. At about 2 pm when the paver turned the corner, the Roadtec MTD was used to pave a 2,900-foot section of the inside southbound lane. About 700 feet after starting to pave with the MTD, the camera battery went dead; therefore, only visual anomalies were documented after this point. About 900 feet from the end of the project the paver slowed down to a crawl due to the slowness of the arrival of the haul trucks; however, the paver never stopped.

DATA COLLECTION

Data collection involved several different processes. Notes of any construction anomalies, such as trucks loaded with a single dump, were taken at the time of paving. The temperature anomalies just behind the paver were noted using the infrared camera at the time of paving. Both texture and IRI measurements were taken using the ARAN van after completion of the test sections; the van was operated at about 25 mph for all projects with the exception of Project 3.-2. Measurements on Project 3-2 (US 82, Reform, AL) surface course were delayed approximately two months due to equipment problems with the Roadware van at the time these sections were constructed. Testing was completed at vehicle speeds of about 45 mph because of the live traffic at the time of testing.

HMA Mat Temperature Measurements

The temperature differences, noted using an infrared camera, were differences in the mat just behind the paver of over 20°F. The operator of the infrared camera sat in the spare driver's seat on the paver (Figure 11) and faced the screed, or hot mat. When a temperature difference was seen, the operator took a picture of the anomaly with the camera, which logs the pictures with the time, and then signaled the manual distance meter operator. Figure 12 is an example that shows a temperature anomaly caused by a paver stop. The manual distance meter operator noted the distance measurement, from the start of paving, and the time the picture was taken. The time noted was used to correlate the distance marks to the infrared pictures. In sections without the MTD, it was common to see two cold spots, or one long cold spot, at the end of each truck of mix.

Figure 11. Infrared Camera Operator and Manual Distance Meter Operator.

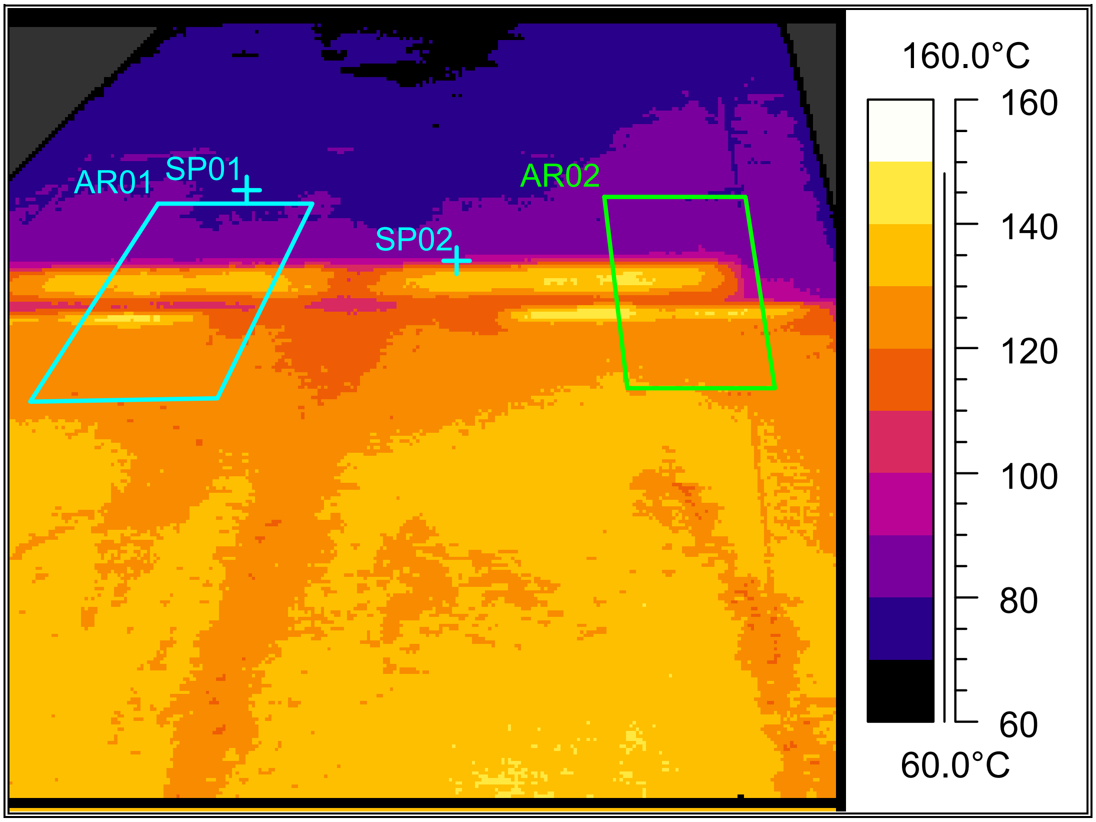

Figure 12. Infrared Image of a Temperature Anomaly (20 minute paver stop).

Texture and IRI Measurements

Three runs (replicates) using the ARAN van were completed for each test section. Both the average texture and IRI was computed for 15-foot long segments; texture was obtained for only the right wheel path while the IRI was obtained in both the left and right wheelpaths.

Most runs were taken at about 25 mph. The event key was used to mark the start, the end and other important points in the section. These marks were used to correlate the van distance measurements, which are called chainage in the ARAN system software, to the manual distance meter.

RESULTS AND DISCUSSION

Data Organization and Preliminary Analysis

Each location and lift had test sections both without a material transfer device and sections with remixing and a MTD. The infrared camera was used to detect mat temperature and locations with temperature differences of 19°F were marked. The marking of these differences included both the distance from the start of paving and the time the anomaly was noted. The time is needed to correlate the distance to the images since the infrared camera logs the images according to time. The ARAN van allowed continuous measurement of IRI and distance from the start of paving. Using this van, the data collection was set to give the IRI averages for each 15-foot section. Each 15-foot length of the test section was divided into two categories: ones that had a temperature difference of greater than 19°F and ones that had more uniform temperature throughout.

Table 5 is an example of the IRI data collected and illustrates how the van measurements are correlated with the location of temperature anomalies. Column 1 is the distance from the beginning of the test section to where a temperature anomaly in the mat was noted. Columns 2 through 5and columns 6 through 9are distance, left wheelpath IRI, right wheelpath IRI and average IRI for mat locations with uniform temperature and with temperature anomalies, respectively.

From 3165 to 3195 feet, no temperature anomalies were observed and the IRI values are recorded in columns 3 through 5. At a distance of 3201 feet, a temperature anomaly was observed across the width of the mat and IRI values for the 3210 ft distance are recorded in columns 7 through 9. The procedure followed was to match temperature anomaly location with the closest 15 foot IRI section.

A long continuous temperature anomaly was noted on the right side of the mat from a distance of 3266 feet to 3559 feet. Left wheelpath IRI corresponding to this distance are recorded in column 3 but right wheelpath and average IRI are recorded in, respectively, columns 8 and 9. Compilation and synthesis of data illustrated in Table 5 allows comparisons to determine differences in left and right wheelpath smoothness and to determine effects of temperature anomalies on smoothness. Any blank cell denotes that no entry is made in that category at that distance.

Table 5. Example of Temperature Anomaly and Smoothness Data.

Distance to Temp. Anomaly	Uniform Temperature				Temperature Anomaly			
ft	Distance ft	Left IRI in/mile	Right IRI in/mile	Avg. IRI in/mile	Distance ft	Left IRI In/mile	Right IRI in/mile	Avg. IRI in/mile
	3165	117	117	117				
	3180	236	282	259				
	3195	230	319	275				
3201					3210	145	150	147
	3225	159	89	124				
	3240	130	107	119				
	3255	95	46	70				
3266*	3270	74					61	68
	3285	87					44	65
	3300	90					63	77
	3315	127					84	105
	3330	65					62	64
	3345	39					60	50
	3360	82					61	71
3375*	3375	83					48	66
	3390	88					66	77
	3405	69					86	78
	3420	76					53	65
	3435	65					40	52
	3450	72					58	65
	3465	115					68	92
3477*	3480	80					67	74
	3495	64					49	56
	3510	50					54	52
	3525	72					76	74
	3540	46					38	42
	3555	79					58	69
3559*	3570	66					57	62
	3585	50	56	53				
	3600	61	36	49				
	3615	35	47	41				

* = anomaly continues to next section

Influence of Material Transfer Devices on Initial Ride Quality

Averages for the entire test section were obtained for each category, non-uniform and uniform, and each of the three individual runs. These are tabulated in Tables 6 through 9 for Projects 1, 2, 3, and 4 (Phenix City, Selma, Reform, and Opelika) respectively. Although averages for each run were computed from numerous IRI measurements (1 per 15 feet), they were treated as an individual measurement in statistical analyses, that is, the n value is equal to three.

Three runs were made with the ARAN van for each test section. The ARAN van collects IRI in both right and left wheelpaths. Average IRI for each run were determined for left, right and combined left and right wheelpaths. Averages for the three runs and overall section averages are shown in Tables 6, 7, 8, and 9 for each of the four projects, respectively.

Table 6. US 280 Phenix City Test Section Details (Project 1).

Section			IRI in inches/mile					
			without MTD			with MTD		
			Left IRI	Right IRI	Avg. IRI	Left IRI	Right IRI	Avg. IRI
Project 1-1 (Mainline)	Total Run	Run 1	63	95	79	66	64	65
		Run 2	60	87	74	66	65	65
		Run 3	62	89	75	65	64	64
		Average	**62**	**90**	**76**	**66**	**64**	**65**
	Uniform	Run 1	58	90	74	66	63	65
		Run 2	55	81	68	66	65	65
		Run 3	57	83	70	65	64	64
		Average	**57**	**85**	**71**	**66**	**64**	**65**
	Non-Uniform	Run 1	82	112	97	61	66	61
		Run 2	79	108	93	57	63	59
		Run 3	79	111	95	65	68	63
		Average	**80**	**110**	**95**	**61**	**66**	**61**
Project 1-2 (Frontage)	Total Run	Run 1	67	70	68	77	100	89
		Run 2	66	72	69	76	102	89
		Run 3	68	73	71	77	106	91
		Average	**67**	**72**	**69**	**76**	**103**	**90**
	Uniform	Run 1	63	65	64	73	93	83
		Run 2	62	68	65	73	95	84
		Run 3	63	69	66	73	98	85
		Average	**63**	**67**	**65**	**73**	**95**	**84**
	Non-Uniform	Run 1	80	85	83	100	144	122
		Run 2	81	86	84	96	145	120
		Run 3	81	88	84	100	150	125
		Average	**81**	**86**	**84**	**98**	**146**	**122**

Table 7. US 80 Selma Test Section Details (Project 2).

Section			IRI in inches/mile					
			without MTD			with MTD		
			Left IRI	Right IRI	Avg. IRI	Left IRI	Right IRI	Avg. IRI
Project 2-1 (Binder)	Total Run	Run 1	66	66	66	55	58	56
		Run 2	65	67	66	56	55	55
		Run 3	65	68	66	55	55	55
		Average	**65**	**67**	**66**	**55**	**56**	**56**
	Uniform	Run 1	61	59	60	52	54	53
		Run 2	58	58	58	53	52	53
		Run 3	59	59	59	51	52	52
		Average	**59**	**59**	**59**	**52**	**53**	**53**
	Non-Uniform	Run 1	71	75	73	85	90	81
		Run 2	73	78	75	91	85	81
		Run 3	71	78	75	94	89	84
		Average	**72**	**77**	**74**	**90**	**88**	**82**
Project 2-2 (Surface)	Total Run	Run 1	99	86	93	66	54	60
		Run 2	100	90	95	73	54	64
		Run 3	102	88	95	69	57	63
		Average	**101**	**88**	**94**	**69**	**55**	**62**
	Uniform	Run 1	93	75	84	64	51	57
		Run 2	92	78	85	69	51	60
		Run 3	93	76	85	66	54	60
		Average	**93**	**76**	**85**	**66**	**52**	**59**
	Non-Uniform	Run 1	102	93	98	74	67	71
		Run 2	105	97	101	89	66	78
		Run 3	108	94	101	75	68	72
		Average	**105**	**95**	**100**	**80**	**67**	**73**
	Difference Underlying Binder	Surface	101	88	94	69	55	62
		Binder w MTD	84	52	68	91	59	75
		IRI_S-IRI_B	16	36	26	-22	-4	-13

Table 8. US 82 Reform Test Section Details (Project 3).

Section			IRI in inches/mile					
			without MTD			with MTD		
			Left IRI	Right IRI	Avg. IRI	Left IRI	Right IRI	Avg. IRI
Project 3-1 (Binder)	Total Run	Run 1	69	68	68	65	52	58
		Run 2	67	67	67	65	51	58
		Run 3	69	68	69	63	53	58
		Average	**68**	**68**	**68**	**65**	**52**	**58**
	Uniform	Run 1	65	68	66	60	46	53
		Run 2	63	67	65	61	46	54
		Run 3	65	67	66	60	49	55
		Average	**65**	**67**	**66**	**60**	**47**	**54**
	Non-Uniform	Run 1	75	68	72	73	59	66
		Run 2	73	68	71	71	57	64
		Run 3	76	69	72	68	59	63
		Average	**75**	**69**	**72**	**71**	**58**	**65**
	Total Run Eastbound Outside Lane	Run 1				47	61	54
		Run 2				48	59	53
		Run 3				48	58	53
		Average				**48**	**59**	**54**
Project 3-2 (Surface)	Total Run	Run 1	48	52	50	41	40	41
		Run 2	49	53	51	42	40	41
		Run 3	48	52	50	41	41	41
		Average	**48**	**52**	**50**	**41**	**40**	**41**
	Uniform	Run 1	46	50	48	40	40	40
		Run 2	46	51	48	40	39	40
		Run 3	46	51	48	40	40	40
		Average	**46**	**51**	**48**	**40**	**40**	**40**
	Non-Uniform	Run 1	68	68	68	64	54	59
		Run 2	67	66	67	63	56	59
		Run 3	65	62	64	64	54	59
		Average	**67**	**65**	**66**	**64**	**55**	**59**
	Difference Underlying Binder	Surface	48	52	50	41	40	41
		Binder w MTD	66	62	64	68	60	64
		IRI_S-IRI_B	-16	-9	-12	-26	-19	-22

Table 9. I-85 Opelika Test Section Details (Project 4).

Section			IRI in inches/mile					
			without MTD			with MTD		
			Left IRI	Right IRI	Avg. IRI	Left IRI	Right IRI	Avg. IRI
(Project 4-1) Binder	Total Run	Run 1	73	65	69	68	57	63
		Run 2	74	66	70	70	57	63
		Run 3	73	66	70	67	58	63
		Average	**73**	**66**	**70**	**68**	**57**	**63**
	Uniform	Run 1	64	56	60	68	56	62
		Run 2	65	57	61	69	56	63
		Run 3	65	58	61	67	58	62
		Average	**65**	**57**	**61**	**68**	**57**	**62**
	Non-Uniform	Run 1	92	83	87	73	74	73
		Run 2	92	85	88	82	65	73
		Run 3	88	84	86	67	69	68
		Average	**91**	**84**	**87**	**74**	**69**	**72**

An examination of Tables 6 through 9 shows the surface mix test section on the Project 1-2 (US 280 frontage road) was the only one where the smoothness without the MTD was, unexpectedly, better than the smoothness with the MTD. A section of the existing frontage road pavement, approximately 1800 feet, was tested prior to overlaying. The average IRI of this section was 162 inches per mile, with some 15-foot section IRI values as high as 1200 inches per mile as shown in Figure 13. This extremely rough portion of the frontage road was part of the section placed with the material transfer device, while the pavement in the section placed without the material transfer device was much smoother. The highly variable roughness of the underlying pavement was thought to be the reason for the unexpected surface IRI measurements, 69.36 inches per mile without the MTD and 89.56 inches per mile with the MTD. The chip seal and the 165 pounds per square yard mix application rate were apparently not sufficient to eliminate the effects of the underlying pavement roughness, which masked any beneficial effects of the MTD.

Project 1-2 (Phenix City frontage road surface) data were not used in computing averages shown in Table 10, nor for analyzing the influence of MTD's, since it was the only project that did not mill the old surface prior to paving. Averages in Table 10 were computed by combining data from all other test sections.

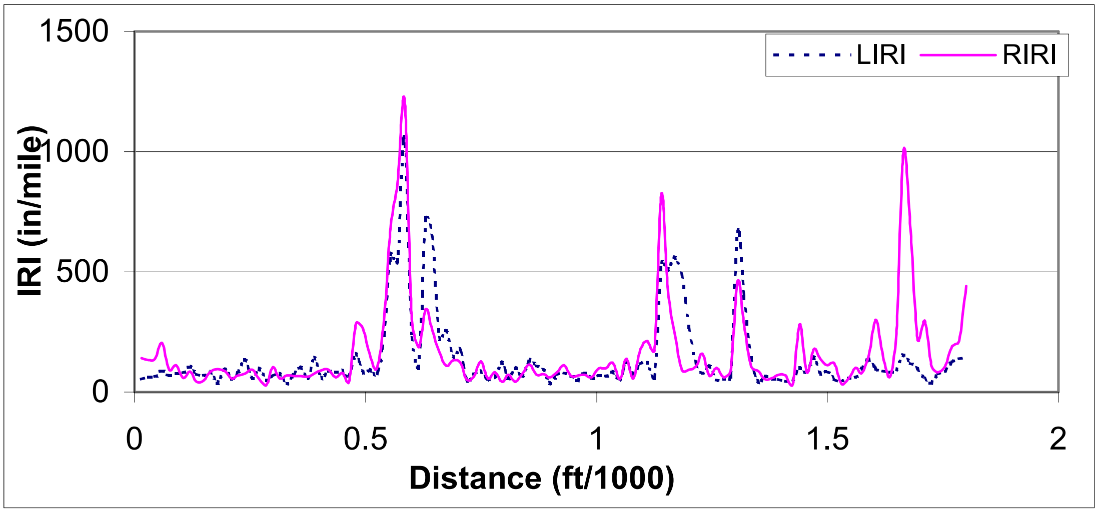

Figure 13. Phenix City Frontage Road Baseline (Project 1-2).

Table 10. Test Section Averages (IRI in inches/mile).

Average of		Average IRI, inches/mile
With MTD		57.37
w/o MTD		70.81
With MTD	Non-Uniform Areas	77.36
	Uniform Areas	60.70
w/o MTD	Non-Uniform Areas	81.59
	Uniform Areas	63.67
Non-Uniform Areas		79.47
Uniform Areas		62.18
Extended Wheelpath IRI		70.55
Opposite Wheelpath IRI		62.01

Some additional testing was done on Projects 2-2 and 3-2 (Selma and Reform surface) test sections. IRI measurements were made on the binder layer before paving to give a baseline for evaluating smoothness improvements for the surface layer. It should be noted that the binder and surface test sections were at different locations on each project. However, the binder layers beneath surface test sections were placed with MTD's and should be comparable with corresponding binder test section layers. For

Project 2 (US 80 Selma), the average IRIs for binder below surface test sections were somewhat larger (67.92 and 74.86 inches/mile) than the average IRI for binder with MTD test section (55.64 inches/mile). For Project 3 (US 82 Reform), the same difference was noted: the average IRIs for binder below the surface test sections were larger (64.34 and 63.58 inches per mile) than the average IRI for binder with the MTD test section (58.14 inches per mile). IRI for binder layers below surface test sections were not included in calculations of test section averages in Table 10 or in subsequent statistical analyses.

Figures 14 and 15 show IRI of binder layers and corresponding IRI of overlying surface layers. Differences between IRI measured on the surface and IRI measured on the binder ($IRI_S - IRI_B$) are shown in Tables 7 and 8, and allow assessment of how much improvement in smoothness is achieved with the surface layer. A comparison of values with and without the MTD allows determination of how much more smoothness improvement might be achieved with a MTD.

A close examination of Figure 14, for Project 2 (US 80 Selma), seems to indicate surface IRI in the section without the MTD may indeed be larger than the binder IRI. IRI differences in Table 7 confirm this observation. The positive ($IRI_S - IRI_B$) in the section without the MTD indicates the surface layer is rougher than the binder layer. This is unexpected and can only be explained by placement and/or compaction problems with the surface layer. The negative ($IRI_S - IRI_B$) differences for the section with the MTD show, as expected, the surface layer is smoother than the underlying binder layer.

An examination of Figure 15, for Project 3 (US 82 Reform), shows the surface layer is much smoother than the underlying binder. The IRI values in Table 8 confirm that the surface layers (50.36 and 59.26 inches per mile) are smoother than the binder layers (64.34 and 63.58 inches per mile). Also seen in Figure 15 is that large spikes in the binder IRI are apparently smoothed out by the surface. For example at the distance of 1050 feet, the binder layer had an IRI of 326.98 inches per mile, while the overlying surface has an IRI of 33.93 inches per mile. In Table 8, both average differences, $IRI_S - IRI_B$, are negative, though the section with the MTD shows a much greater differential (-22.34 inches per mile) than the section without the MTD (-12.22 inches per mile).

The presence of the MTD seems to make a significant improvement in the smoothness of the overlying surface layer. Subsequent statistical analysis will indeed show this to be the case.

Table 8 for Project 3 (US 82 Reform) contains several rows of data labeled Binder, Total Run, and Eastbound Outside Lane. This layer was placed in the morning, with the MTD, prior to placement of the binder test sections but no temperature measurements were made. Binder test sections were placed on the adjacent westbound inside lane beginning at about noon. This additional testing was done to record IRIs that more accurately reflect the benefits of the MTD. In the binder test section in the westbound lane placed with the MTD, mix delivery was so sporadic that continuous paver movement was not possible and long stops were frequent. The total run averages of IRI in Table 8 indicate the eastbound was somewhat smoother (53.53 inches/mile) than the corresponding westbound (58.14 inches/mile). Data from the eastbound binder was not used in computing section averages in Table 10, in analyzing the effects of the MTD nor in analyzing the effects of temperature anomalies; none were measured. But, the data was used in analyzing the effects of screed extensions.

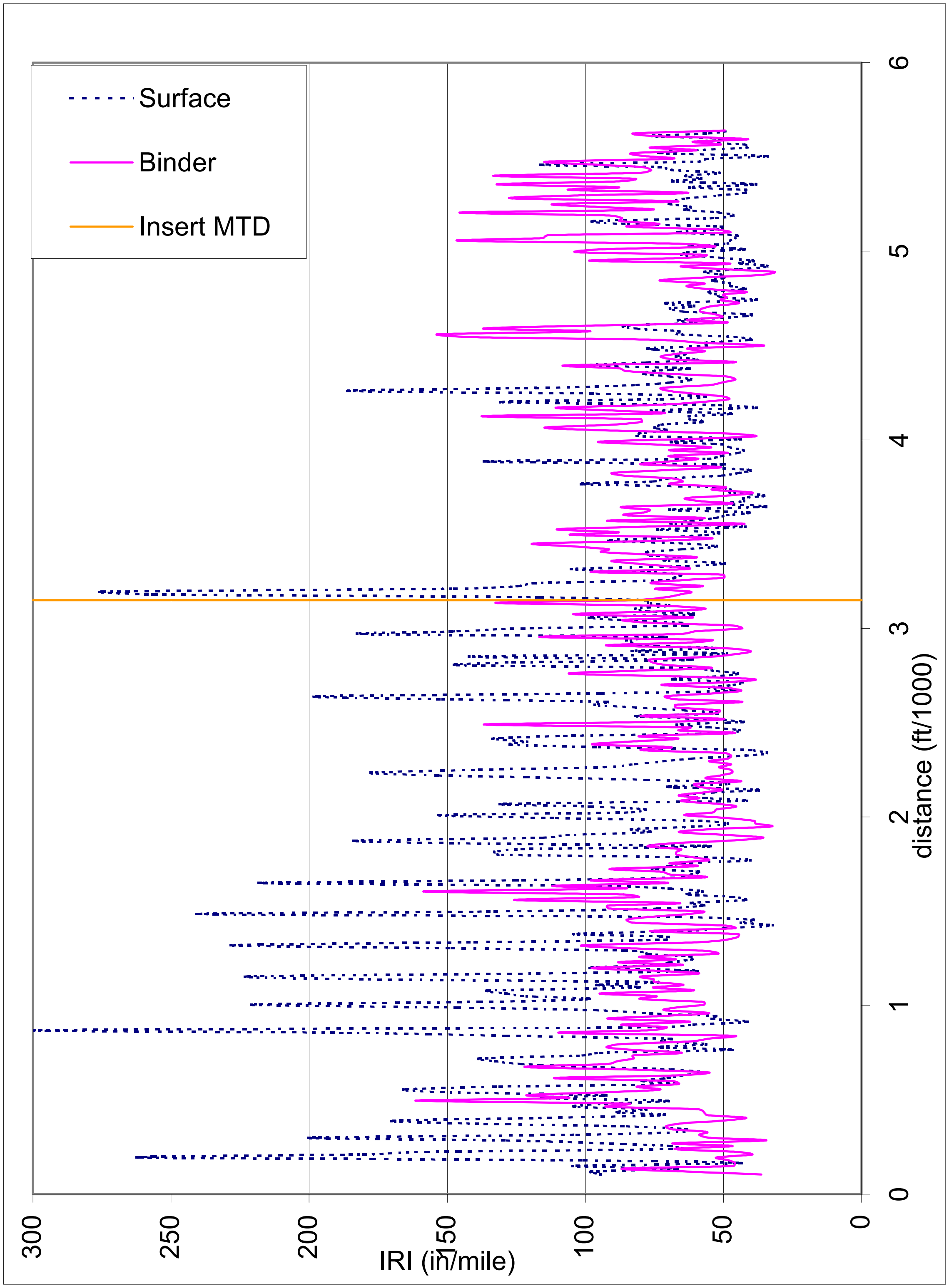

Figure 14. Selma Baseline Comparison (Project 2).

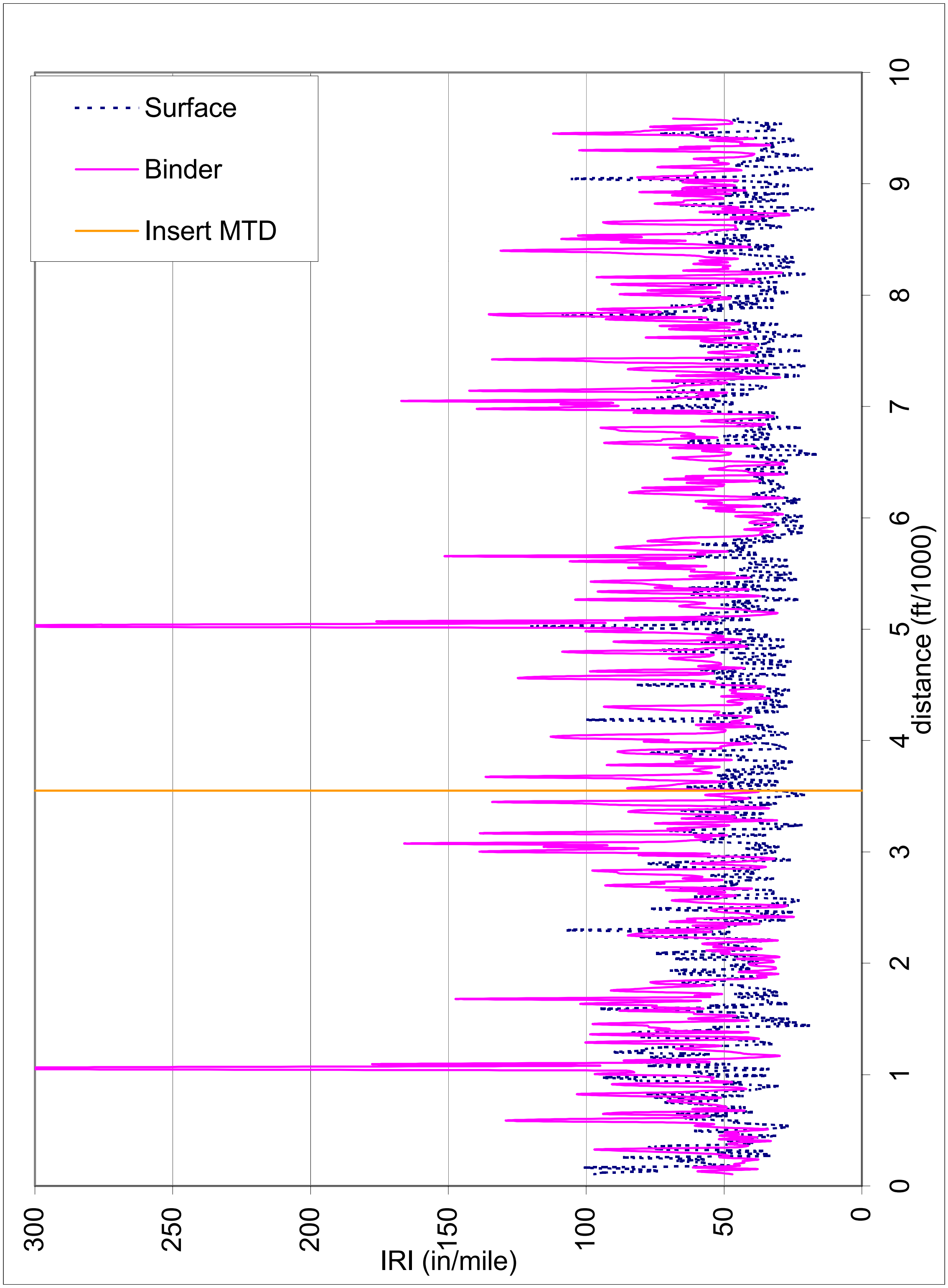

Figure 15. Reform Baseline Comparison (Project 3).

Averages for all sections in Table 10 demonstrate the effects of (1) the MTD, (2) temperature anomalies (uniform and non-uniform) and (3) screed extensions (extended and opposite wheelpath). Comparisons in rows 1 and 2 show that average IRI with the MTD are smaller than IRIs without the MTD. Comparisons in rows 3 through 8 show that average IRIs where temperature anomalies were observed (non-uniform areas) are larger than IRIs where mat temperatures were more uniform. The comparison in rows 9 and 10 shows that IRI in wheelpaths on the side with a screed extension or with the larger screed extension are greater than IRI in wheelpaths on the side without a screed extension or with the smaller screed extension. The statistical significance of differences will be examined in the following section.

Statistical Analyses

Since analyses will be testing differences between averages of the three runs with different treatments, such as left to right wheelpath and mark to no mark comparisons, the t-test for means was chosen for the analysis. The t-test was conducted using the software in the Analysis Toolpak of Microsoft Excel. This same test was used for comparisons across all sites to compare the computed t statistic with the t critical value for a confidence level of 95%. Means were considered to be significantly different if the absolute value of the computed t statistic was greater than the absolute value of t critical.

The comparison to determine the effect of the material transfer devices used the t-test assuming equal variance or the t-test assuming unequal variance. Equality of variances was tested using the one-tailed F test with a confidence level of 95%.

The two tailed, paired t-test was used for the comparison between wheelpaths (effects of screed extension) and the comparison between temperature differences since the treatments to be compared used the same data source, i.e. IRI measurements on the same mat. Thus the samples were not truly independent of one another. The degrees of freedom for each comparison were the number of values in a category minus one.

To illustrate the application of the paired two-sample t-test, the US 280 Left and Right IRI frontage road surface measurements with the MTD will be used. In this section, the right wheelpath is the extended wheelpath. Using the data found in Table 6, the hypothesis test of equality of mean IRI values, with and without the MTD, is presented in Table 11. The analysis concludes that the IRI in the wheel path on the side with the screed extension (right) is significantly larger than the IRI in the opposite (left) wheelpath.

Table 11. Example of Paired t-test.

u_1 = Population mean IRI without MTD		u_2 = Population mean IRI with MTD
Hypothesis	$H_0 = u_1 = u_2$	$H_1 = u_1 \neq u_2$
Extended (right) IRI w/o MTD (inches/mile)	Opposite (left) IRI w MTD (inches/mile)	d_i = difference (inches/mile)
100.32	76.74	23.58
101.97	75.97	26.00
105.65	76.73	28.92
Mean d = $(\sum d_i)/(n)$ = 78.50 / 3 = 26.167 inches/mile		
$s_d = \sqrt{(\sum(d_i - \text{mean d})^2/(n-1))}$ = 7.1497 inches/mile		
Test Statistic: t = mean $d*\sqrt{n} / s_d$ = 16.9		Two tailed t critical: t_{cr} = 4.30
Since $\lvert t \rvert > \lvert t_{cr} \rvert \Rightarrow$ Reject H_0 $\therefore$ Difference in means is significant		

Influence of Material Transfer Device on Ride Quality

An F-test for variances was used to evaluate the uniformity of the IRI measurements within each wheel path and test section. The results of this analysis are shown in Table 12. Since each run has the same beginning and ending, variance is a result of different longitudinal paths being tracked with each run. The results show that, for most sections, the variance is smaller for sections with the MTD. This shows that there is less transverse variation in the mat when a material transfer device is present.

Table 12. F-test results.

Section		with MTD Variance	w/o MTD Variance	F stat	F critical	Equal Variances?
US 280	Mainline	0.16	8.09	51.28	19.0	No
US80	Binder	0.04	0.39	0.102	0.053	No
	Surface	4.36	1.90	0.435	0.053	No
US 82	Binder	0.08	0.59	7.08	19.0	Yes
	Surface	0.004	0.038	9.35	19.0	Yes
I 85	Binder	0.09	0.164	0.548	0.053	No

The t-test assuming unequal variances was used to determine if the variance in ride quality (i.e., IRI) within a test section was influenced by the use of a MTD. The complete results of the evaluation of the influence of material transfer devices in Table 13 show that, for every comparison, the addition of a MTD into the paving train resulted in a significantly smoother pavement. For each mix type at each project, average IRI values were from the three runs of the ARAN van.

Table 13. t-test Results for Effect of MTD.

Section		with MTD AIRI	w/o MTD AIRI	t stat	t critical	Significantly Different ?
US 280	Mainline	65	76	6.73	4.30	Yes
US80	Binder	56	66	27.67	4.30	Yes
	Surface	62	94	22.17	3.18	Yes
US 82	Binder	58	68	20.82	2.78	Yes
	Surface	41	50	79.65	2.78	Yes
I 85	Binder	63	70	34.93	4.30	Yes

Non-Uniformity in HMA Mat Temperatures and Initial Ride Quality

The analysis in the previous section showed the MTD has a significant beneficial effect on pavement smoothness. It is speculated that one of the primary reasons for this is the MTD provides more uniform temperature mix at a more uniform rate which results in more uniform mat temperature. Mat temperature measurements with the infrared camera will be used to investigate mat temperature uniformity.

The 15-foot sections with a temperature difference of greater than 19°F were separated from the sections with uniform temperatures. These 15-foot sections correspond to sections where IRI values were computed. The total number of sections in the entire test section and those sections with non-uniform temperatures were counted. Then the percentage of the test sections with non-uniform temperature was calculated. As seen in Table 14, the MTD reduced the percentage of sections that contain temperature differences in all but one case: the US 82 Reform binder (Project 3-1).

Project 3-1 (Reform binder) test sections did not follow the expected pattern. The percentage of sections with temperature variations with the MTD (40.6%) was slightly higher than the percentage without the MTD (37.8%). Weather conditions were very unfavorable; temperature around 50^{o}F, light breezes and overcast with light drizzle. Mix delivery was so sporadic that, even with the MTD, there were frequent and often long stops of the paver. These conditions negated any beneficial effects of the MTD in producing uniform mat temperature.

Table 14. Percentage of Test Sections with a Temperature Variation.

Location		Percentage of 15-foot lengths with Non-Uniform Temperatures, %	
		without MTD	with MTD
Phenix City	Mainline	21.8	3.7
	Frontage	23.1	14.5
Selma	Binder	46.7	10.3
	Surface	63.1	20.6
Reform	Binder	37.8	40.6
	Surface	12.4	5.6
Opelika	Binder	33.6	5.0
AVERAGE		**34.1%**	**14.3%**

A second analysis matched sections with a high IRI (100 inches/mile or greater) to sections with a temperature difference of more than 19°F. An average of only seven 15-foot sections had IRI values over 100 in/mile when a MTD was used compared to twenty four 15-foot sections without a MTD. When 15-foot sections had IRI values over 100 in/mile, between 50 and 80% of these sections also had non-uniform temperatures.

Table 15. Percentage of High IRI Sections with a Temperature Difference.

Location		Number of 15-foot Sections with Non-Uniform Temperatures out of Number of 15-foot Sections with IRI > 100 in/mile			
		without MTD		with MTD	
		No. Non-Uniform to No. with IRI> 100	Percent (%)	No. Non-Uniform to No. with IRI> 100	Percent (%)
Phenix City	Main	22 out of 31	71.0	0 out of 9	0.0
Selma	Binder	15 out of 17	88.2	10 out of13	76.9
	Surface	61 out of 63	96.8	5 out of 7	71.4
Reform	Binder	10 out of13	76.9	1 out of 2	50.0
	Surface	2 out of 3	66.7	1 out of 1	100
Opelika	Binder	19 out of19	100	2 out of 9	22.2
AVERAGE		**20 out of 24**	**83.27**	**3.7 out of 7**	**53.42**

A final analysis compared IRI from 15-foot sections with non-uniform temperatures to those with uniform temperatures. A paired t-test was used to determine if IRI values were statistically lower when using a MTD. Table 16 shows that in all but one case (Project 1-1), the use of a MTD significantly reduces the IRI. This table also shows that non-uniform temperature areas of the HMA pavement have significantly higher IRI than when paving operations place mixtures with a uniform temperature.

Table 16. Paired t-test Results for Effect of Temperature Variations.

Section			IRI in Non-Uniform Areas in /mile	IRI in Uniform Areas in/mile	t stat	t critical	Significantly Different?
US280	Main	MTD	61	65	2.70	4.30	No
		No MTD	95	71	32.54	4.30	Yes
	Front	MTD	122	84	45.06	4.30	Yes
		No MTD	84	65	57.48	4.30	Yes
US80	Binder	MTD	82	53	25.08	4.30	Yes
		No MTD	74	59	13.09	4.30	Yes
	Surface	MTD	73	59	7.91	4.30	Yes
		No MTD	100	85	15.64	4.30	Yes
US 82	Binder	MTD	65	54	8.74	4.30	Yes
		No MTD	72	66	27.45	4.30	Yes
	Surface	MTD	59	40	891.5	4.30	Yes
		No MTD	66	48	13.60	4.30	Yes
I 85	Binder	MTD	72	62	5.87	4.30	Yes
		No MTD	87	61	26.55	4.30	Yes
MTD			77	61	77	61	Yes
No MTD			82	64	82	64	Yes
Overall Comparison			**80**	**62**	**79**	**62**	**Yes**

Evaluation of Screed Extension Effect on Ride Quality

Although not related to the use of an MTD, consistent effects of screed extensions were noted when analyzing smoothness data. Consistent differences were noted between IRI in wheelpaths on the side where screeds were extended or where screed extensions were the largest and IRI in the opposite wheelpaths. Screed extensions are most often used and/or larger toward the outside or shoulder. Correspondence of direction and/or magnitude of screed extension and left and right wheel path IRI measurements will depend on the lane being paved. Most screeds today are ten feet wide, and since most paving lane widths are wider than ten feet, screed extensions are common and, therefore, differences in wheelpath roughness will likely be common.

The t-test analysis, to determine the effect of screed extension is summarized in Table 17. In every case except Project 2-1 (US 80 Selma binder) sections and Project 3-2 (US 82 Reform surface) without the MTD, the wheelpath with the extension had a higher IRI than the other wheelpath. However, in these three cases the differences are not significant.

For the 12 cases where extended wheelpath IRI are higher, 10 are statistically significantly higher and 2 are not. The 2 where the extended wheelpath IRI are not statistically significantly higher are Project 1-1 (US 280 Phenix City binder) with a MTD, and Project 3-1 (US 82 Reform binder) without a MTD. A comparison also shows that the overall extended wheelpath average IRI, 70.55 inches per mile, was significantly different than the other wheelpath average IRI, 62.01 inches per mile. These comparisons indicate that extension of the screed to one side will likely create rougher pavement on that side of the mat.

Table 17. Paired t-test Results for Effect of Screed Extension.

Section			Extended IRI	Other IRI	t stat	t critical	Significant Difference?
US280	Main	MTD	66	64	3	4	No
		No MTD	90	62	18	4	Yes
	Front	MTD	103	76	17	4	Yes
		No MTD	72	67	6	4	Yes
US80	Binder	MTD	55	56	1	4	No
		No MTD	65	67	3	4	No
	Surface	MTD	69	55	6	4	Yes
		No MTD	101	88	9	4	Yes
US 82	Binder	MTD	65	52	9	4	Yes
		No MTD	68	68	2	4	No
	East-bound	MTD	59	48	11	4	Yes
	Surface	MTD	40	41	4	4	No
		No MTD	52	48	34	4	Yes
I 85	Binder	MTD	68	57	8	4	Yes
		No MTD	73	66	15	4	Yes
Overall Comparison			**70.55**	**62.01**	**71**	**62**	**6**

Influence of MTD on Surface Texture

The mean texture depth (in millimeters) average, variance, standard deviation, and coefficient of variation are documented in Table 18. Statistics for uniform temperature areas are also shown in Table 18.

The average mean texture depth, variance, standard deviation, and coefficient of variation were also calculated for each run separately and the data are documented in Table 18.

Project 3 had various problems that occurred on the site including bad weather, length of the project, lack of haul trucks, a four-foot screed extension, and a power system failure in the van at the end of testing. Therefore, these sections were eliminated from the texture analysis.

Within-Laboratory Precision

Figure 16 shows the standard deviation is dependent upon the mean texture. Therefore, the coefficient of variation (CV) was evaluated as the most appropriate statistic to represent variability.

Table 18. Display of All Data and Data from only Uniform Temperature Areas.

				All Data					Uniform Temperature Areas				
Project	Shuttle Buggy	Total Chainage (feet)	Total Number of Stops	Average Texture (mm)	Number of Data Points (n)	variance (s^2)	Standard Deviation (mm)	Coefficient of Variation (%)	Average Texture (mm)	Number of Data Points (n)	variance (s^2)	Standard Deviation (mm)	Coefficient of Variation (%)
1-1 binder	No	3139	5	0.853	512	0.0149	0.1222	14.33	0.836	449	0.0138	0.1176	14.07
	yes	2230	4	0.633	351	0.0091	0.0954	15.07	0.633	346	0.0091	0.0952	15.04
1-2 surface	No	3997	11	0.163	643	0.0007	0.0274	16.81	0.162	558	0.0008	0.0274	16.91
	yes	4100	7	0.140	577	0.0007	0.0255	18.21	0.140	560	0.0007	0.0255	18.21
2-1 binder	No	2950	12	0.600	473	0.0053	0.0729	12.15	0.593	392	0.0048	0.0693	11.69
	yes	2950	4	0.622	470	0.0057	0.0755	12.14	0.617	423	0.0052	0.0722	11.70
2-2 surface	No	3140	12	0.506	504	0.0096	0.0978	19.33	0.490	410	0.0076	0.0870	17.76
	Yes	2825	2	0.533	374	0.0056	0.0746	14.00	0.533	350	0.0055	0.0739	13.86
3-1 binder	No	1813	14	0.233	295	0.0040	0.0636	27.30	0.229	225	0.0038	0.0619	27.03
	Yes	1130	3	0.216	179	0.0047	0.0688	31.85	0.207	127	0.0036	0.0598	28.89
3-2 surface	No	4201	17	0.216	672	0.0027	0.0517	23.94	0.208	552	0.0027	0.0521	25.05
	Yes	6022	6	0.239	963	0.0011	0.0326	13.64	0.238	880	0.0011	0.0325	13.66
4-1 binder	No	3877	30	0.618	621	0.0098	0.0991	16.04	0.586	420	0.0074	0.0859	14.66
	Yes	2880	1	0.560	463	0.0092	0.0961	17.16	0.550	429	0.0077	0.0875	15.91
												average CV =	**14.73**

Note: Shaded areas not included in averages or other analysis

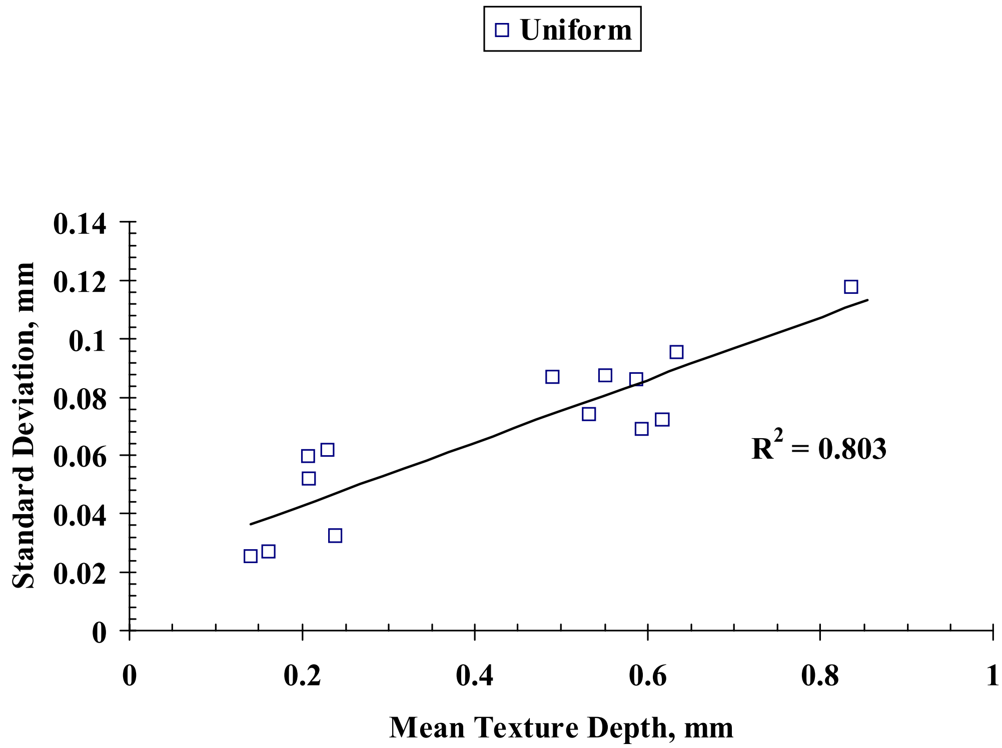

Figure 16. Average Mean Texture versus Average Standard Deviation.

Coefficient of Variation

Coefficient of variation (CV) is a unitless measurement of the population that expresses variability (Rao 1998).

$$CV = \frac{\sigma}{|\mu|} \text{ x } 100$$

where: σ = standard deviation

$|\mu| =$ absolute value of the population mean

The three highest CV values shown in Figure 17 are associated with Projects 3-1 and 3-2 (the only projects paved during the winter months). If these values are not considered, the average coefficient of variation about 15%.

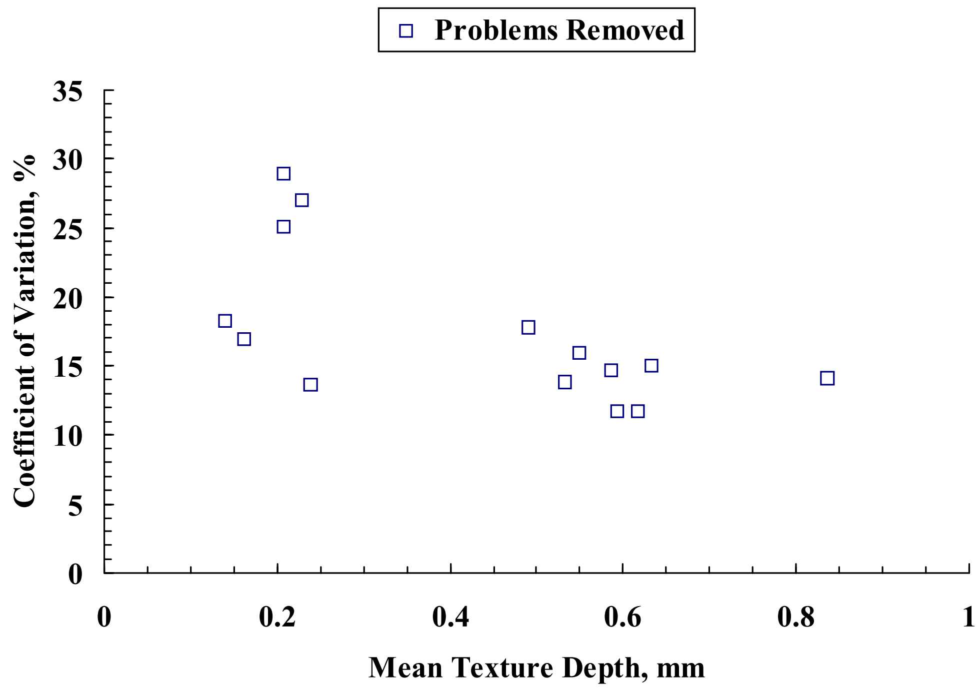

Figure 17. Mean Texture Depth versus Coefficient of Variation.

From the data of problems removed with an MTD without Project 3-1 documented on Table 18, an average coefficient of variation, 14.6%, was calculated. From the slope of Figure 18 the coefficient of variation should be 14.1 % and is probably different from the calculated average because of rounding errors; therefore, for simplicity 15% was used in the calculations. A new standard deviation was then found for each site separately by rearranging the formula for the coefficient of variation and solving for the standard deviation.

$$\sigma = CV * \mu$$

Using the calculated standard deviation, maximum and minimum limits were set for each site separately according to the formulas displayed below. Anything above or below these limits are areas predicted to have a significant amount of gradation segregation and possibly need maintenance work before the end of its designed life cycle. Areas with statistically higher texture will likely show accelerated pavement distresses while areas with statistically lower texture will possibly have safety problems such as slick surfaces. Using ± two standard deviations ensures that 95% of the data will be within the mean maximum and minimum limits.

*Maximum Mean Texture Depth = Average Mean Texture Depth + 2 * Calculated Standard Deviation*

*Minimum Mean Texture Depth = Average Mean Texture Depth - 2 * Calculated Standard Deviation*

Table 19 displays limits for each mix. The limits are also displayed as lines on the graph of chainage versus average texture depth in Figure 20 for project 4-1 without an MTD. Six out of the eight paver stops resulted in non-uniform areas that will most likely result in premature pavement distress. All eight stops resulted in mean texture depths above one standard deviation. On these figures, paver stops are indicated by a "PS".

Table 19. Mean Texture Depth Limits.

Project	Shuttle Buggy	Average Texture (mm)	STD Dev from CV (mm)	Ave Texture +/- one STD Dev (mm)	Ave Texture +/- two STD Dev (mm)
1-1 binder	No	0.836	0.125	0.711 – 0.961	0.585 - 1.087
	Yes	0.633	0.095	0.538 – 0.728	0.443 - 0.823
1-2 surface	No	0.162	0.024	0.138 – 0.186	0.113 - 0.211
	Yes	0.140	0.021	0.119 – 0.161	0.098 - 0.182
2-1 binder	No	0.593	0.089	0.504 – 0.682	0.415 - 0.771
	Yes	0.617	0.093	0.524 – 0.710	0.432 - 0.802
2-2 surface	No	0.490	0.074	0.417 – 0.564	0.343 - 0.637
	Yes	0.533	0.080	0.453 – 0.613	0.373 - 0.693
3-1 binder	No	0.229	0.034	0.195 – 0.263	0.160 - 0.298
	Yes	0.207	0.031	0.176 – 0.238	0.145 - 0.269
3-2 surface	No	0.208	0.031	0.177 – 0.239	0.146 - 0.270
	Yes	0.238	0.036	0.202 – 0.274	0.167 - 0.309
4-1 binder	No	0.586	0.088	0.498 – 0.674	0.410 - 0.762
	Yes	0.550	0.083	0.468 – 0.633	0.385 - 0.715

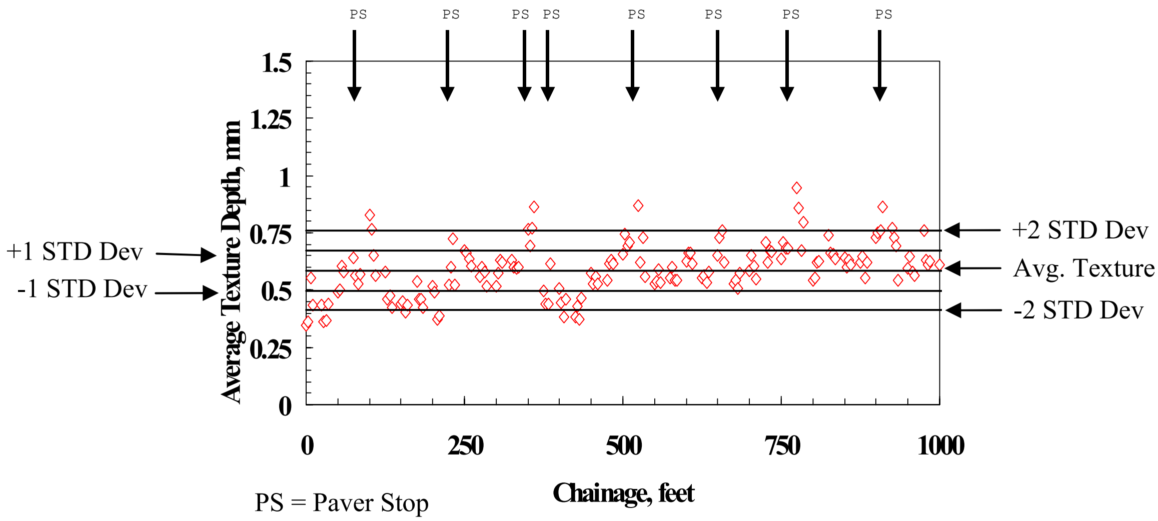

Figure 18. Example of Mean Texture Limits from Project 4-1 without an MTD.

Segregation Ratios

Even though mean texture depth is mix dependent, the ratio of the texture depth for a point to the average mean texture depth of the section will indicate the level of segregation according to NCHRP Report 441, "Segregation in Hot-Mix Asphalt Pavements" (Stroup-Gardiner, 2000). The ratios for low, medium, and high segregation are displayed in Table 20 with the respective standard deviations. For data lower than the mean texture depth a low ratio limit of 0.75 is set which corresponds to possible areas of loss of skid resistance in the pavement mat.

Table 20. Segregation Limits set by NCHRP Report 441.

	Amount of segregation		
	Low	medium	high
ratio limits	1.16 - 1.56	1.57 - 2.09	>2.09
standard deviation	0.15	0.22	0.42

From the data gathered the ratio of the texture depth for above/below one standard deviation to the average mean texture results in ratios of 0.85-1.15 and for two standards deviations is 0.70-1.30. Therefore, the area below two standard deviations with the ratio of 0.70 is similar to the ratio of 0.75 found in Report 441. A ratio of 1.30 is about in the middle of low segregation range from Report 441 and is the point considered to need maintenance in this current research study.

Non-Uniform Texture

Potential maintenance work will probably need to occur when the data is above and below the texture limits already established in Table 20. Table 21 displays sample texture data from Project 3-1 without an MTD. The areas highlighted in blue are above the maximum mean texture depth. For this location, the length above two standard deviations is 25 feet. Five feet is added to both sides of the anomaly to ensure that the problem will be properly repaired if maintenance is needed, which will result in a potential maintenance length of 35 feet. The same concept is used for areas below the minimum mean texture depth. Highlighted in yellow are two data points that are below the allowable limit for this mix. The two highlighted points have four feet of non-segregated pavement between them; therefore, these four feet are included to create one potential maintenance area. This results in 22 feet of pavement below two standard deviations and a potential maintenance area of 32 feet.

Table 21. Sample Texture Data from Project 3-1 without an MTD.

Chainage (ft)	Texture for run 1 (mm)	Texture for run 3 (mm)	Texture for run 2 (mm)	Avg Mean Texture Depth (mm)	Variance	Standard Variation
1107	0.216	0.193	0.373	0.261	0.010	0.098
1110	0.254	0.267	0.228	0.250	0.000	0.020
1125	0.527	0.218	0.232	0.326	0.030	0.175
1128	0.294	0.192	0.585	0.357	0.042	0.204
1132	0.309	0.255	0.345	0.303	0.002	0.045
1135	0.500	0.399	0.252	0.384	0.016	0.125
1150	0.161	0.262	0.250	0.224	0.003	0.055
1153	0.157	0.175	0.234	0.189	0.002	0.040
1157	0.218	0.168	0.189	0.192	0.001	0.025
1160	0.184	0.242	0.240	0.222	0.001	0.033
1175	0.170	0.192	0.187	0.183	0.000	0.012
1178	0.147	0.152	0.198	0.166	0.001	0.028
1182	0.192	0.150	0.266	0.203	0.003	0.059
1185	0.189	0.230	0.199	0.206	0.000	0.021
1200	0.133	0.132	0.203	0.156	0.002	0.041
1203	0.233	0.166	0.145	0.181	0.002	0.046
1207	0.130	0.134	0.174	0.146	0.001	0.024
1210	0.267	0.153	0.143	0.188	0.005	0.069
1225	0.276	0.190	0.179	0.215	0.003	0.053

The following are general explanations of the terms used in Table 22. The "number of potential places for maintenance activities" is the number of times the texture data exceeds the set limits. For maintenance work to be performed properly five feet is added to both sides of the anomaly; therefore, the "length of potential maintenance work" is equal to the length of pavement statistically higher/lower than the established limits plus ten feet. The length of potential maintenance work divided by the number of places of potential maintenance is equal to the "average length of potential maintenance." The "percent of the project that will potentially need maintenance" is equal to the length of potential maintenance divided by the total length of the project.

Table 22. Potential Maintenance Work.

Project	Shuttle Buggy	Total Length of Projects (feet)	Total Number of Stops	Length of Pavement two Standard Deviations Higher: Length of Pavement Statistically Higher (ft)	Length of Potential Maintenance Work (ft)	Number of Places of Potential Maintenance Activities	Average Length of Potential Work (ft)	% of Project that will Potentially need Maintenance	Length of Pavement two Standard Deviations Lower: Length of Pavement Statistically Lower (ft)	Length of Potential Maintenance Work (ft)	Number of Places of Potential Maintenance Activities	Average Length of Potential Work (ft)	% of Project that will Potentially need Maintenance
1-1 binder	No	3139	5	266	426	16	26.6	13.6	123	163	4	40.8	5.2
	Yes	2230	4	173	243	7	34.7	10.9	194	264	7	37.7	11.8
1-2 surface	No	3997	11	124	244	12	20.3	6.1	43	73	3	24.3	1.8
	Yes	4100	7	346	456	11	41.5	11.1	115	175	6	29.2	4.3
2-1 binder	No	2950	12	57	137	8	17.1	4.6	0	0	0	---	0.0
	Yes	2950	4	57	97	4	24.3	3.3	0	0	0	---	0.0
2-2 surface	No	3140	12	138	248	11	22.5	7.9	43	73	3	24.3	2.3
	Yes	2825	2	30	60	3	20.0	2.1	0	0	0	---	0.0
3-1 binder	No	1813	14	229	389	16	24.3	21.5	85	155	7	22.1	8.5
	Yes	1130	3	181	291	11	26.5	25.8	62	112	5	22.4	9.9
3-2 surface	No	4201	17	565	815	25	32.6	19.4	177	367	19	19.3	8.7
	Yes	6022	6	563	783	22	35.6	13.0	59	159	10	15.9	2.6
4-1 binder	No	3877	30	518	788	27	29.2	20.3	137	237	10	23.7	6.1
	Yes	2880	1	261	401	14	28.6	13.9	108	178	7	25.4	6.2

For the areas of pavement above two standard deviations, except for project 1-2 surface and project 3-1 binder, the percent of the project that will potentially need maintenance is higher when a MTD is part of the paving train. Project 3-1 had already been excluded during calculation phase because of high variability in the texture data; therefore, it is not surprising to see a number of areas that may need maintenance. In Figure 19, only project 1-2 had slightly more potential areas of accelerated maintenance areas when paving with an MTD compared to paving without one. Project 1-2 possibly had abnormal results because of weather problems (thunderstorms), traffic interruptions, and the number of screed extensions required for business entrances to the road.

For areas below two standard deviations, one of the projects will potentially not require maintenance work according to the texture data. The percent of the project that will potentially require maintenance is approximately the same for one project. Three of the remaining five projects will potentially require more maintenance when an MTD was incorporated. Two of these projects, 1-2 and 3-1, had already been disregarded for the above reasons. Project 1-1 was also expected to have similar results with and without an MTD because of the amount of stops that occurred was about the same, even though the length of project was much shorter when an MTD was used.

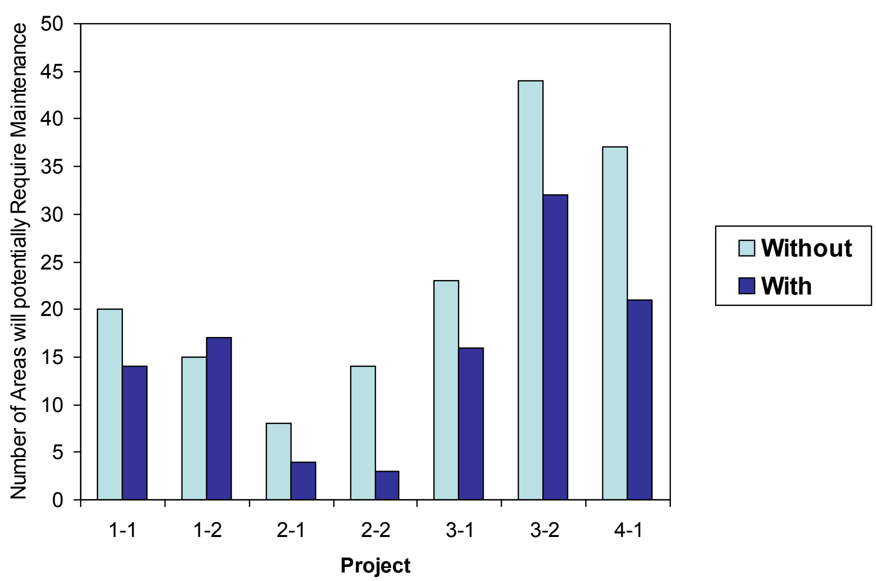

Figure 19. Bar Graph of the Number of Places with Possible Accelerated Maintenance Activities.

Influence of Type of MTD on Texture Uniformity

Figure 20 shows typical localized areas of non-uniform texture, seen as spikes in the texture profile, when a MTD in not used. The paver stops are associated with the end of the mix that is incorporated into the mat when the paver wings are flipped. Figure 21 shows the typical texture pattern seen when the Blaw-Knox paver is used; Project 3 was the only construction project that used this type of MTD. The Blaw-Knox MTD has the remixing auger in the surge bin rather than prior to the surge bin as with the Roadtec MTD. Figure 21 shows that while the Blaw-Knox MTD eliminates the extreme changes in texture seen in Figure 20, there is still a consistent sinusoidal pattern to the texture with the peaks in the sine wave occurring every approximately 250 feet. This is the same interval that is associated with the distance paved with one truck (Figure 20). Given this pattern, which cannot be explained by random material variation, the conclusion can be drawn that this MTD is not thoroughly remixing the HMA material. That is, there is still some end-of-truck segregation occurring in this project. Since only one Blaw-Knox MTD was evaluated in this study, it is not clear if this finding is specific to the equipment used in this study or is typical of this type of MTD.

Project 3-2 without MTD

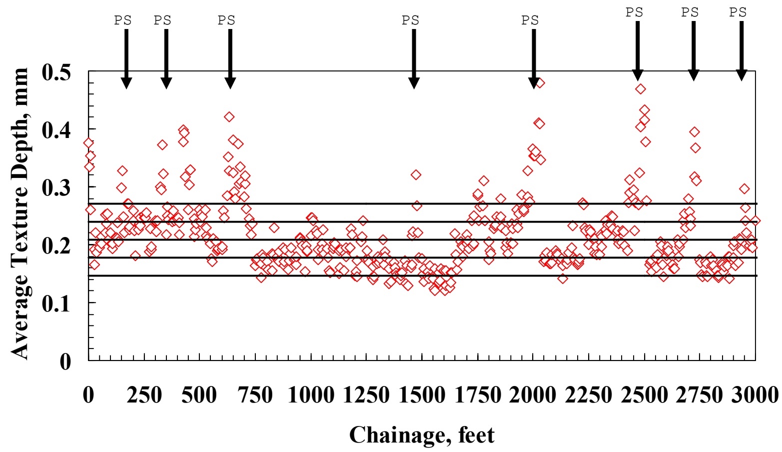

Figure 20. Typical Non-Uniform Texture when a MTD is Not Used (Project 3-2).

Project 3-2 with MTD

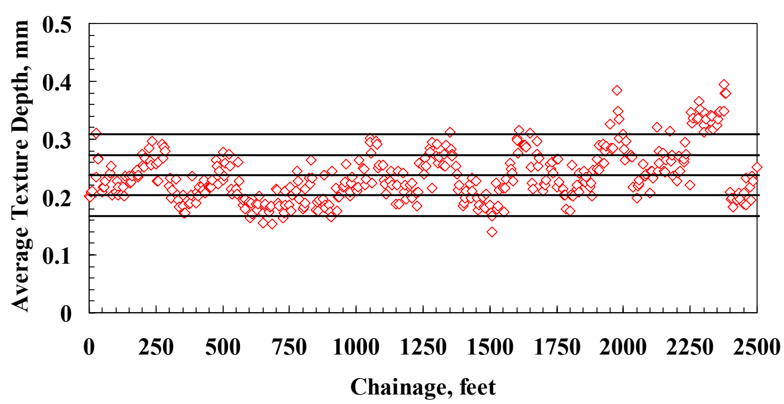

Figure 21. Typical Texture Pattern When the Blaw-Knox MTD Used (Project 3-2).

CONCLUSIONS

Based on observations during paving operations and analysis of the data collected, the following general conclusions were drawn:

- A material transfer device improves the smoothness of the mat constructed and reduces the number of areas in the HMA mat with significantly higher textures (i.e., areas with potentially accelerated pavement distresses).
- Insufficient mix delivery rates to a project that result in excessive stopping of the paver can negate the beneficial effect of a material transfer device. Both IRI and surface texture variations are increased with the number of stops.
- The extension of the screed to one side seems to have a significant negative effect on the smoothness of the pavement on that side of the mat. That is, the longitudinal area associated with the interface between the fixed screed and the start of the extension is associated with increased roughness.
- Sections with temperature differences (>19EF) are significantly rougher than sections that have more uniform temperature.
- A smaller percentage of a test section contains a temperature difference (>19EF) when a material transfer device is present.
- Locations with a high IRI (100 inches per mile or greater) are more likely to correspond to a locations with a temperature difference of greater than 19°F when no material transfer device is present.
- The standard deviation of the mean texture depth measurement is strongly correlated with the average mean texture depth. A coefficient of variation of 15% is best used for estimating anticipated mean texture depth variability on a given project.
- When the old surface is milled, the number of potential maintenance areas required (as estimated using changes in texture) is less when an MTD is part of the paving train.
- While a more uniform texture is achieved with the inclusion of any MTD in the HMA paving train, there appears to be less remixing with the Blaw-Knox MTD than with the Roadtec MTD. However, since only one Blaw-Knox MTD was

included in this study, further evaluations should be made to confirm this observation.

REFERENCES

Alabama Department of Transportation. Standard Specifications for Highway Construction. Montgomery: Alabama Department of Transportation, 2001.

Blaw-Knox the Paving Manual: Guidelines for Paving Professionals. Ingersoll-Rand, 2000.

Choubane, Bouzid, Ronald McNamara and Stacy Scott. Ride Acceptance Testing: Survey of Current State Practices. State Materials Office: Florida Department of Transportation, 2001.

Fernando, Emmanuel G. "Applicability of New Flexible Pavement Smoothness Specification for Asphalt Overlays." Transportation Research Record 1575, Transportation Research Board (1997): 18-24.

Georgia Department of Transportation. Section 400 – Hot Mix Asphaltic Concrete Construction. Atlanta: Georgia Department of Transportation, 1998.

Janoff, Michael S. Pavement Smoothness. Information Series 111. NAPA: Lanham, 1991.

Ksaibati, Khaled, Rick Staigle and Thomas M. Adkins. "Pavement Construction Smoothness Specifications in the United States." Transportation Research Record 1491, Transportation Research Board (1995): 27-32.

Massucco, J. and Cagle, J. "Getting Smoother Pavement." Public Roads 62.5 (1999): 27-31.

McGhee, K.K. "Factors Affecting Overlay Ride Quality." Transportation Research Record 1712, Transportation Research Board (2000): 58-65.

Roadtec SB 2500B." Roadtec, Inc. 10 Dec 2002 <http://www.roadtec.com/literature/default.htm>.

Smith, K.D., T.E. Hoerner, and M.I. Darter. "Effect of Initial Pavement Smoothness on Future Smoothness and Pavement Life." Transportation Research Record 1570, Transportation Research Board (1997): 60-69.

Smith, K.L., K.D. Smith, L.D. Evans, T.E. Hoerner, and M.I. Darter. Smoothness Specifications for Pavements. Washington DC: Transportation Research Board, 1997.

Stroup-Gardiner, M. and E.R. Brown. Segregation in Hot-Mix Asphalt Pavements. National Cooperative Highway Research Program Report 411. National Academy Press, Washington D.C., 2000.

Rao, P.V. Statistical Research Methods in the Life Sciences. University of Florida: Duxbury Press, 1998.

Asphalt Contractor. "The Verdict is In: Proper Paving Techniques Impact Quality." Asphalt Contractor. February 2000.

Wagner, Christopher T. "A Study of Asphalt Concrete Mix Design, Construction Procedures, and Their Associated Affects on Pavement Smoothness." Thesis. Auburn University, 2001.